STANDARD MODEL TESTS AT THE TEVATRON

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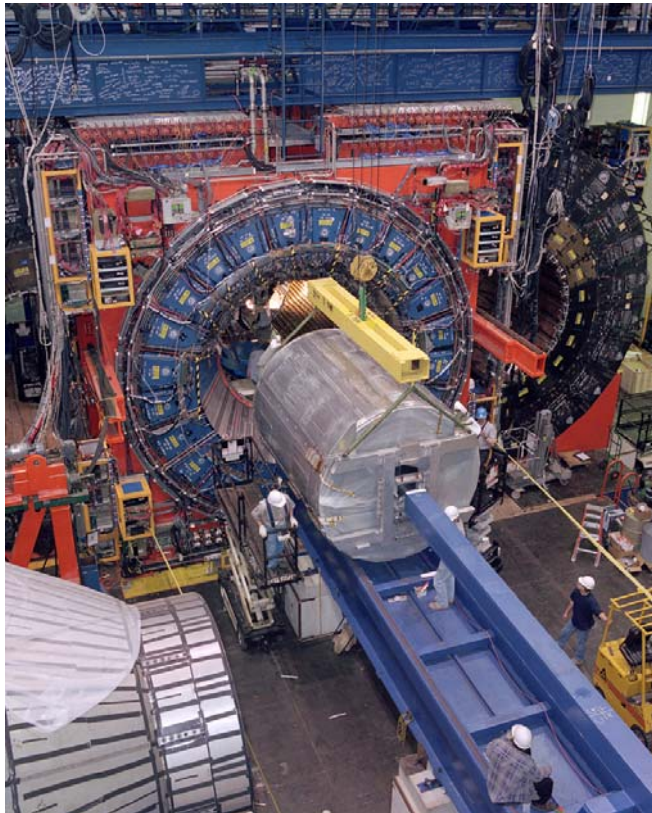


Outline

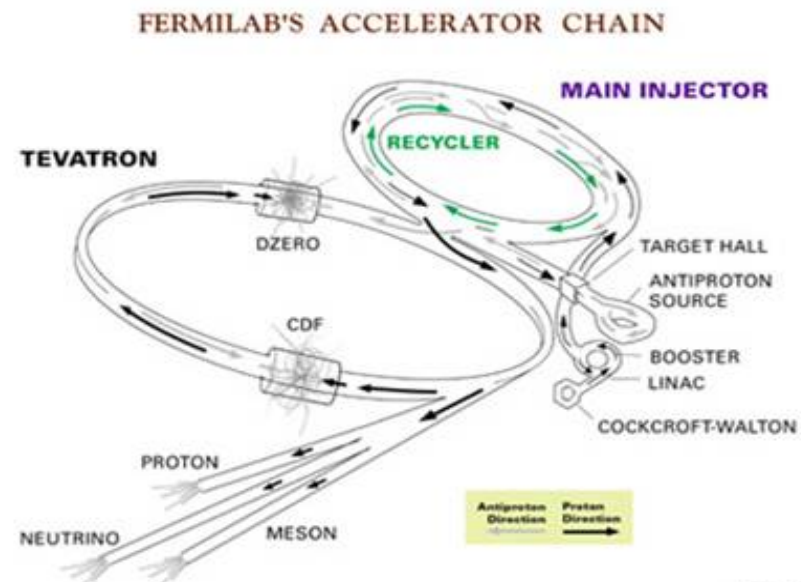
- The experimental facilities:
  - The Tevatron
  - The CDF and D0 detectors
- Top quark physics:
  - Pair production cross section
  - Top mass measurements and prospects
  - Single top production
- W and Z boson physics:
  - W & Z boson cross sections
  - W boson mass & width
  - W production asymmetry
  - WW, WZ, ZZ pair production
- A global look at the Standard Model:
  - the Tevatron perspective

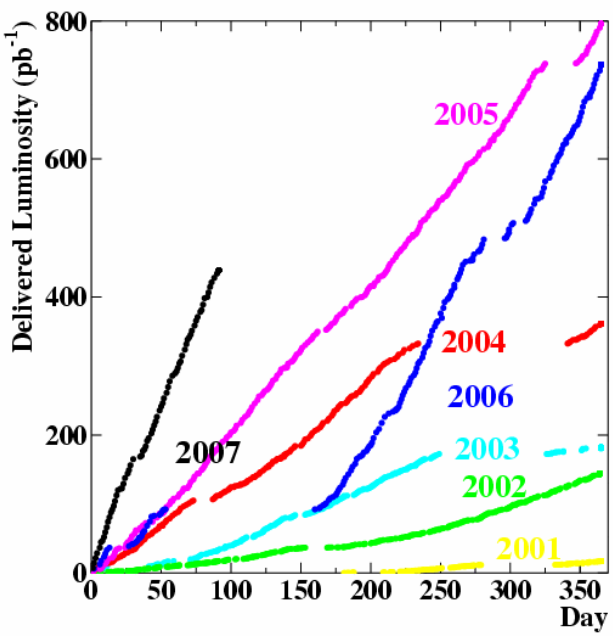
The Tevatron collider

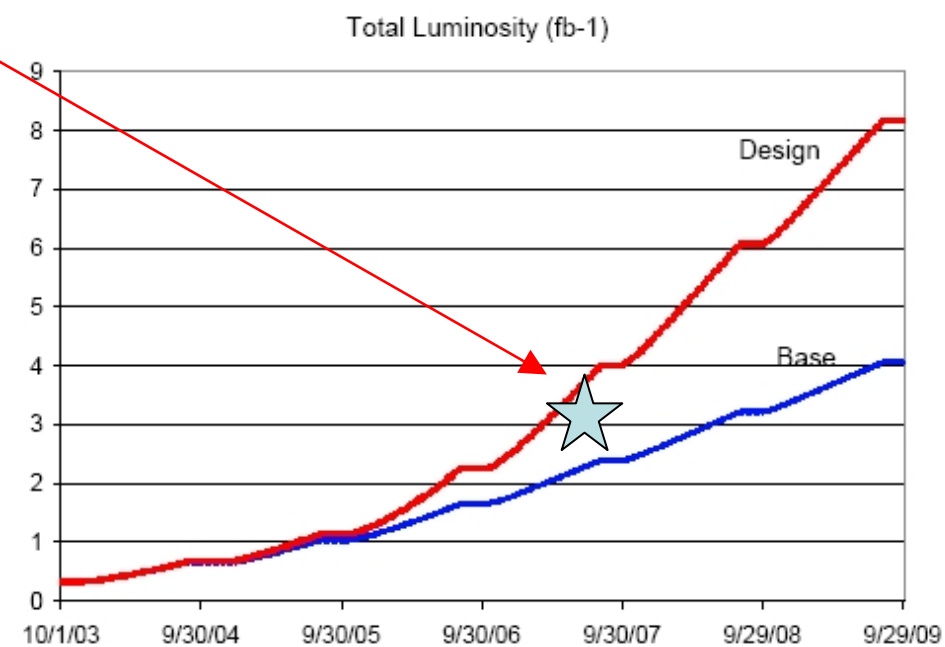
The Tevatron is a superconducting ring for proton-antiproton collisions. It provides **1.96 TeV collisions** at a bunch-crossing rate of 392 ns

Performances have kept improving since the start of Run II. So far, **3/fb** of collisions have been delivered to CDF and D0.

- **7/fb** can be foreseen by the end of 2009.
- Current record luminosity: **L = 2.92 E32 cm^{-2} s^{-1}**







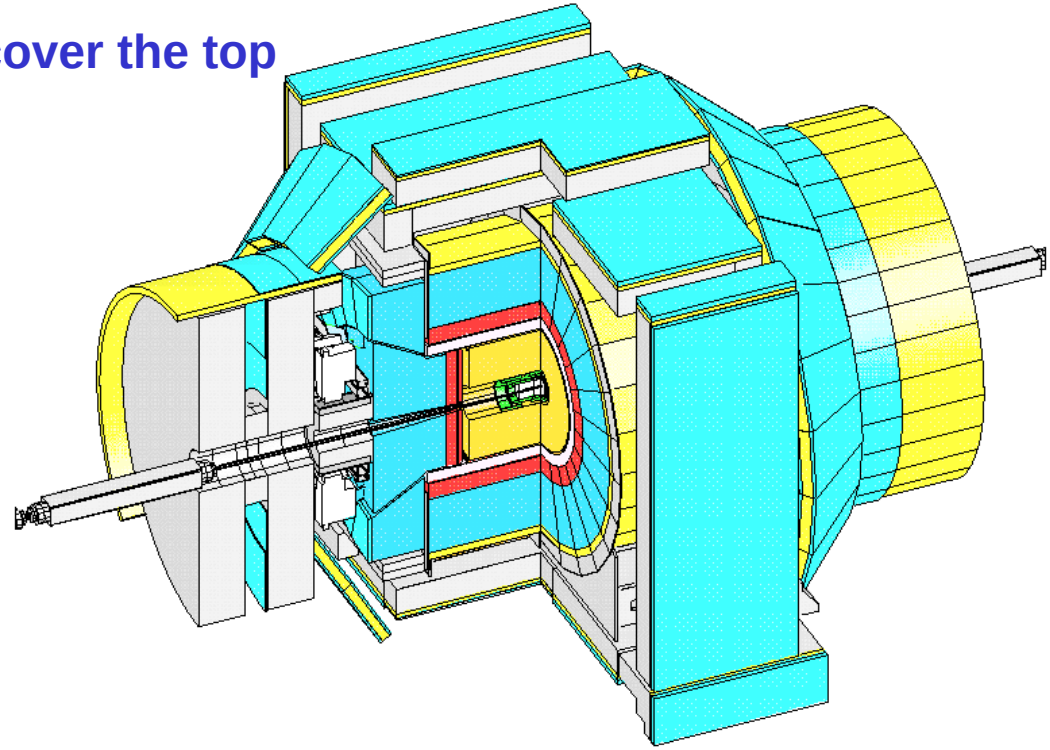
The CDF detector

A magnetic (B=1.4T) all-purpose detector, composed of:

- L00+SVX+ISL: 7 silicon layers
- COT, central tracker to $|\eta|<1.1$
- EM calorimeters for electrons ($|\eta|<2$) and photons; HAD calorimeters
- An extended system of muon chambers covering $|\eta|<1.5$

Original structure designed to discover the top quark 25 years ago

It has achieved a LOT more!

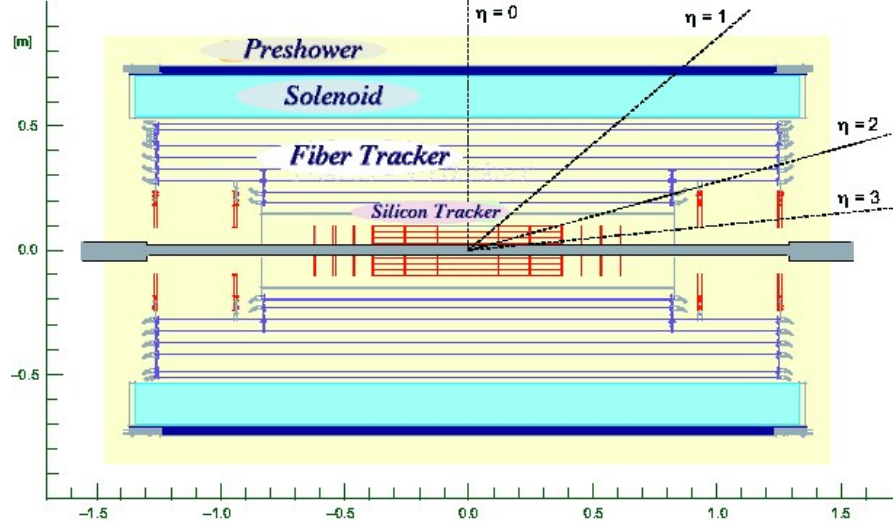


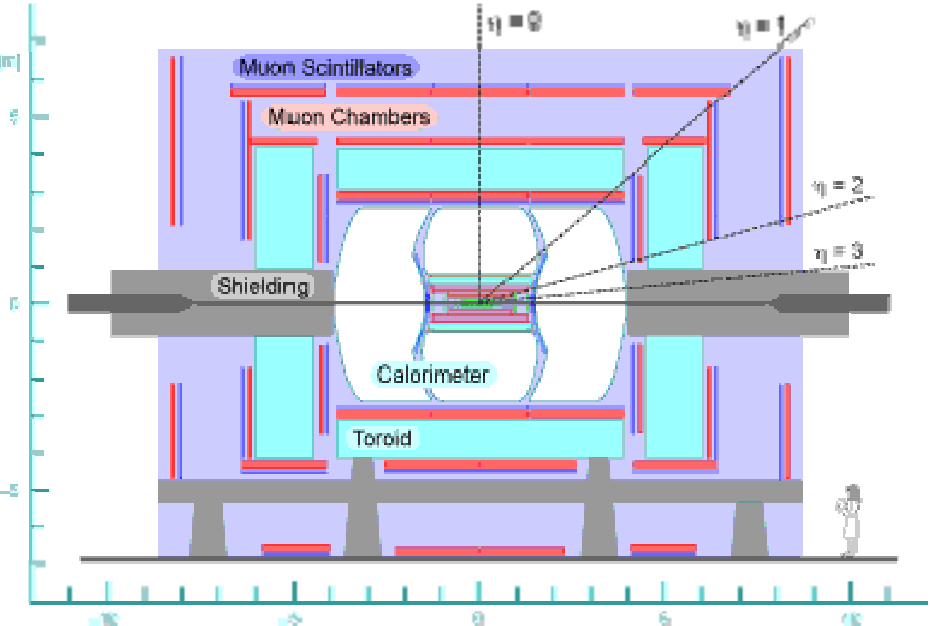
The D0 Detector

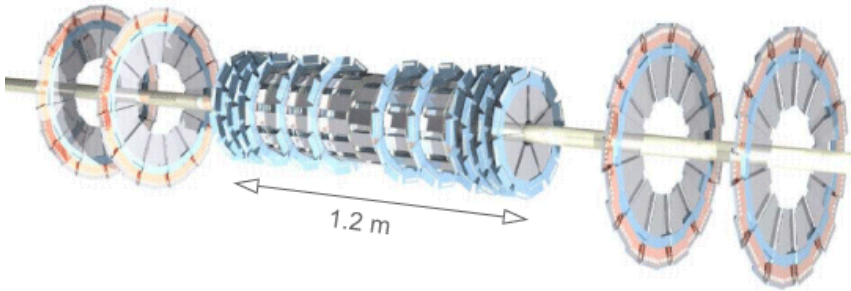
CDF's younger brother is also a complete and redundant system, endowed with

- a hermetic silicon detector
- a compact scintillating fiber tracker
- 2.0 Tesla axial B field
- a hermetic U/liquid Ar calorimeter
- Extended muon coverage

The tracker allows high performance b-jet tagging out to |η|<2.0







Top Quark Physics

The top quark is a very special particle:

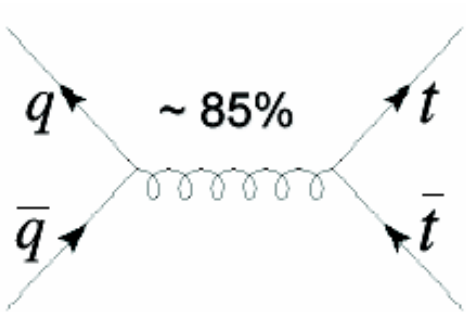
- Heavier than the W boson (M_t=171 GeV)
- Decays before hadronizing: Γ_t=1.5 GeV > Λ_{QCD}
  - Can be studied free from QCD effects
  - Polarization at production can be studied in decay distributions (depolarization time $\tau_d \sim M_t/\Lambda^2$ is much longer)
- Heavy mass has large impact on radiative EW corrections through Higgs coupling
  - Helps gaining insight on the inner consistency of the SM
  - A 1 GeV precision on M(t) carries the same info on M(h) as a 7 MeV precision on M(W)

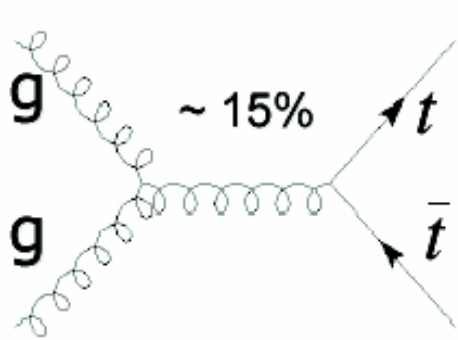
Open questions:

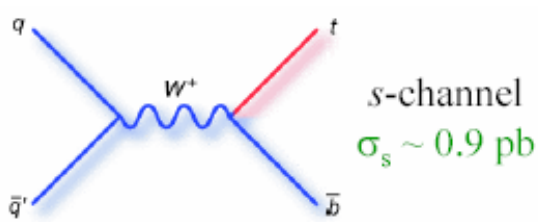
- Why is the top mass so large ?
- Why is its Yukawa coupling, $\mathbf{Y_{top} = sqrt(2)M_{top}/v}$ very close to unity ?
- If the top is so heavy, is it special in other ways ?

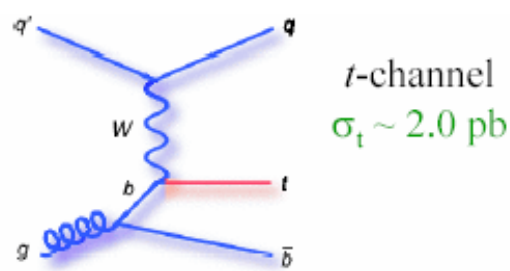
Production of top at the Tevatron

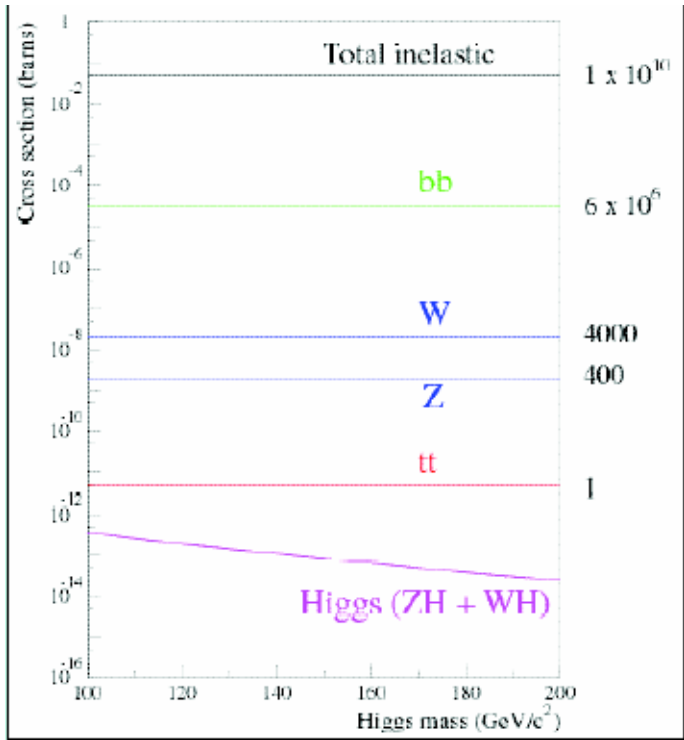
- Production of top-antitop pairs occurs by quark-antiquark annihilation (85%) or gluon fusion (15%)
- The theoretical cross section (NNLO) is 6.1 pb →$1/10^{10}$ collisions
  - → 4 events per hour, **several thousands** already collected
- Top pair decay produces two W and two b-quarks → three main signatures
  - **Dilepton**: two high Pt leptons, two b-jets, missing energy from two neutrinos
  - **Single lepton**: one high-P_t lepton, two b-jets, two additional jets, missing energy
  - **All-hadronic**: two b-jets, four additional jets
- Single top production is not irrelevant (3 pb), but its *signature is way less striking* → so far only "evidence", but a definitive confirmation is expected soon











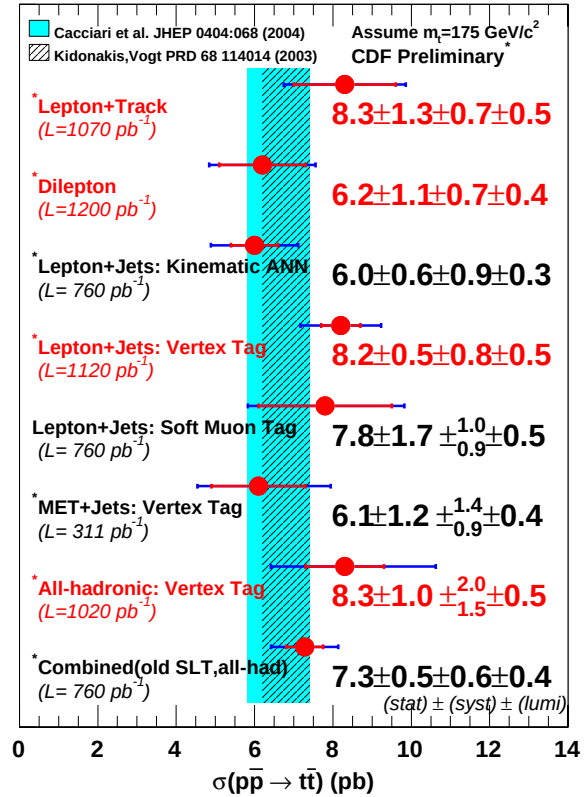
Measurements of σ_{tt}

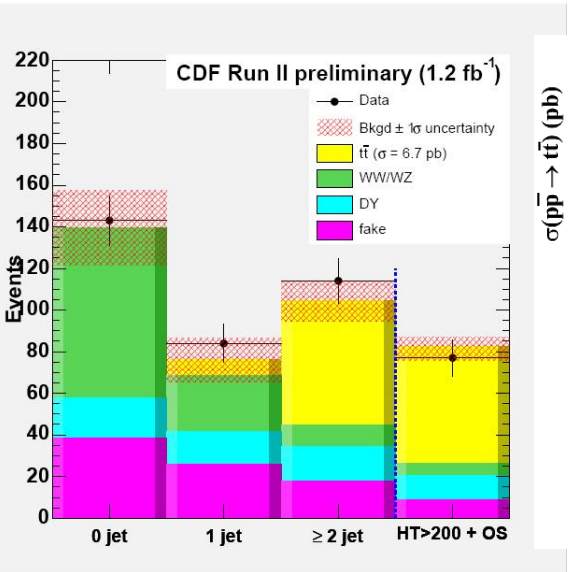
The top pair production cross section error is now of about 12% (CDF), similar to the theoretical one

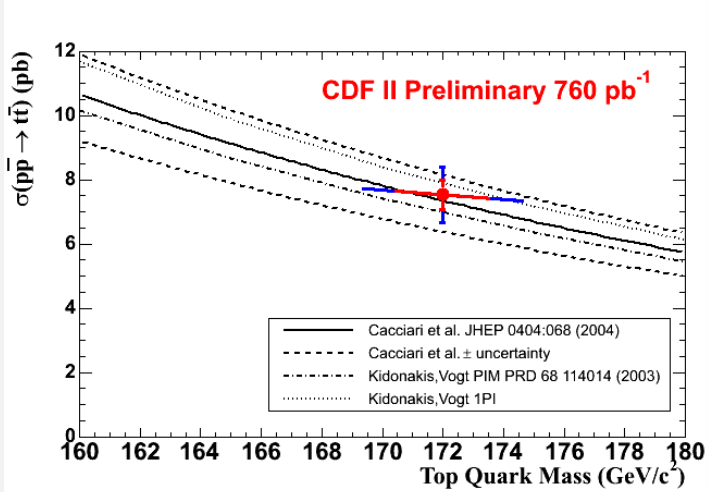
→ high-precision test of perturbative QCD calculations (now at NNLO – Cacciari, Kidonakis)

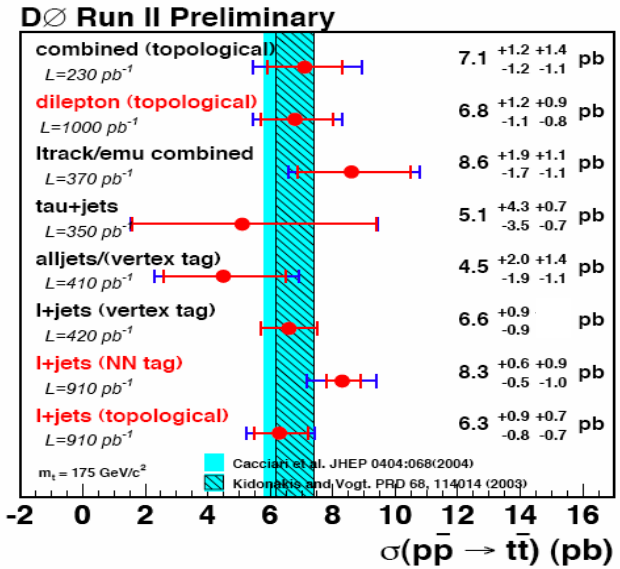
→ proves our understanding of high-Pt data

The cross section is measured in all final states: it is the first step of any analysis using the data to study the details of top quark properties.

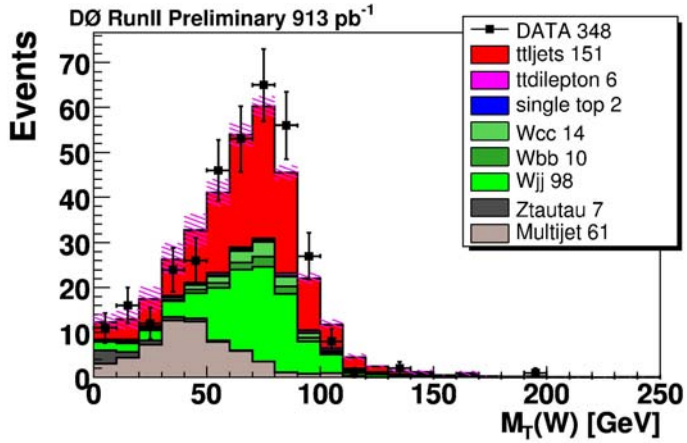




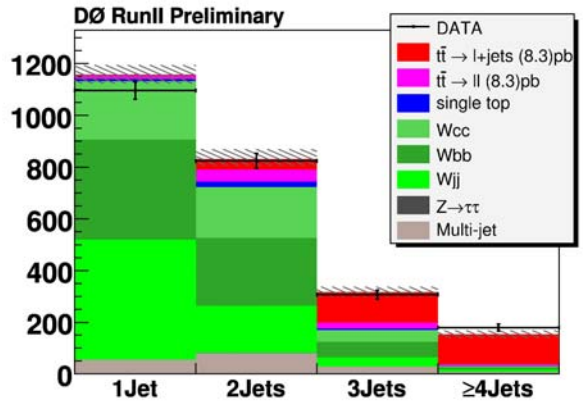




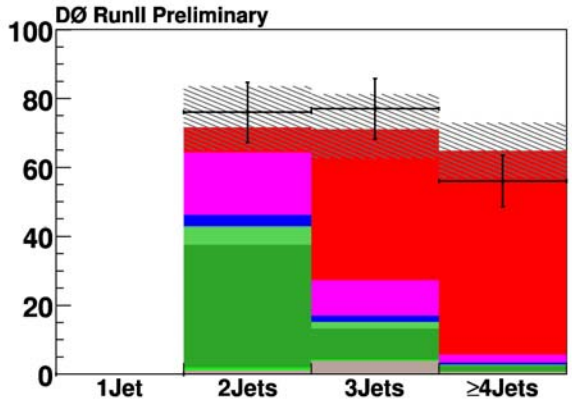
Example: Single lepton σ_{tt}, D0



D0 measured the top pair cross section in 913/pb with one high-P_t e or μ, missing transverse energy from the neutrino, and 3 or 4 jets.
At least one jet is required to be b-tagged by a very performant Neural Network b-tagging algorithm (ε = 54%, fake rate =1%)



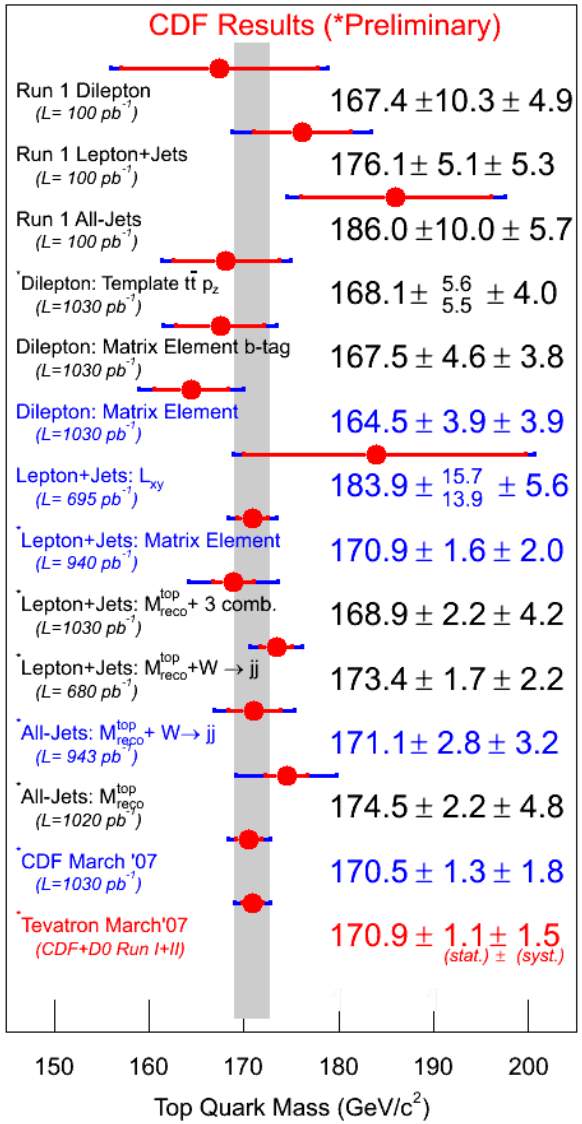
- ***Physics backgrounds*** *are estimated with Monte Carlo simulations (MC)*
- ***fake lepton backgrounds*** *are determined from looser data selections*
- ***W+jets with fake b-tags*** *are estimated with b-tagging probabilities parametrized from MC and rescaled to match the data.*



Event yields are fit in 8 categories (e/μ; 3/4 jets; 1/ ≥2 b-tags) to derive the final result:

$$\sigma_{p\bar{p}\to t\bar{t}+X} = 8.3^{+0.6}_{-0.5}(\text{stat})\ ^{+0.9}_{-1.0}(\text{syst})\ \pm 0.5(\text{lumi})\ \text{pb}$$

Top mass measurements



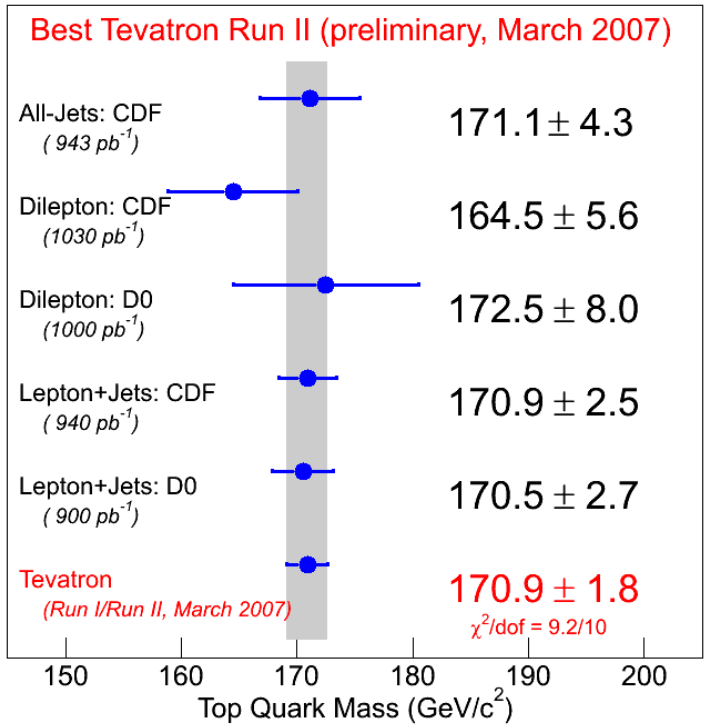
A big effort is ongoing in D0 and CDF to determine this fundamental quantity with the best possible precision in all available final states

Multi-fold strategy:

→ a careful reduction of systematics from jet E scale
→ use of advanced fitting methods
→ use of as many samples as possible
→ combine result of different techniques

The top quark mass is now known with a precision that was thought unreachable at the Tevatron only a few years ago:

$\Delta M/M<1.1\%$!!



Example: CDF, single-lepton channel

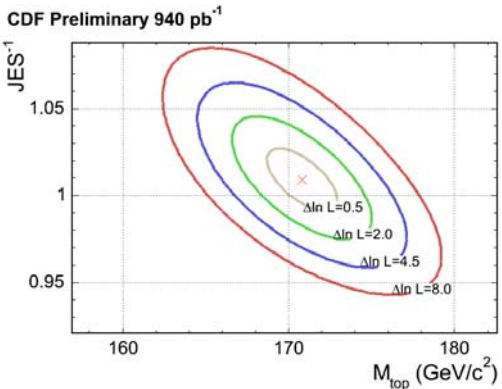
A global likelihood using the top pair production **matrix element** and transfer functions (parton→jet) is used by the CDF analysis in the lepton+jets sample, with a dataset of 0.94/fb so far analyzed.

***166 tt candidates** of W+3,4 jets (>=1 b-tag) are selected with standard cuts:*

lepton	$E_T > 20$ GeV (e), $p_T > 20$ GeV/c (μ)
jets	$E_T > 15$ GeV, $\|\eta\| < 2.0$
missing E_T	missing $E_T > 20$ GeV
b-tag	≥ 1 jet coming from secondary vertex
QCD veto	$0.5 < \Delta\phi < 2.5$ (missing $E_T < 30$ GeV)

The mass of the jet pair from W→jj is used to obtain an internal constraint to the error on the jet energy scale(JES).

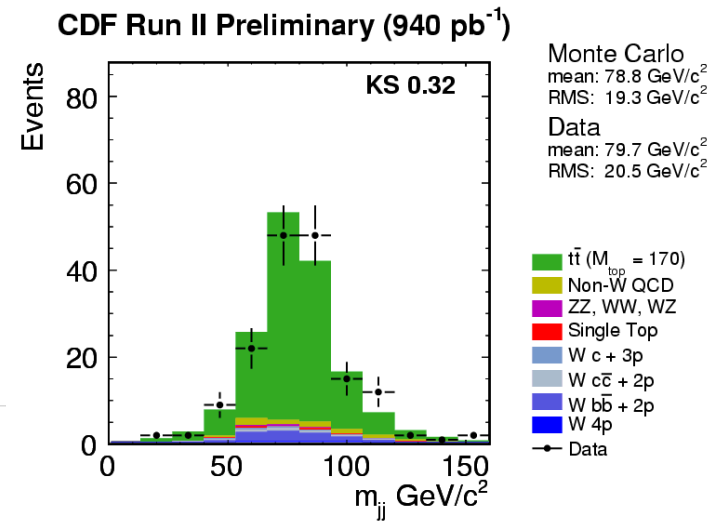
M_{top} and the systematics on JES are jointly extracted from the products of single-event likelihoods.

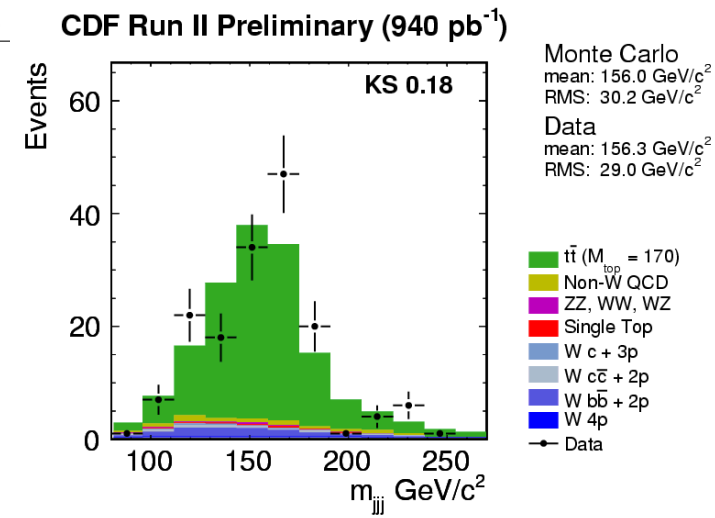


*The result is the **world's single best measurement**:*

$$M_{top} = 170.9 \pm 2.2\ (\text{stat+JES}) \pm 1.4\ (\text{syst})\ \text{GeV/c}^2$$

$$= 170.9 \pm 2.6\ \text{GeV/c}^2$$





Top mass measurement prospects

Besides a x5-x10 increase in statistics, several improvements are possible:

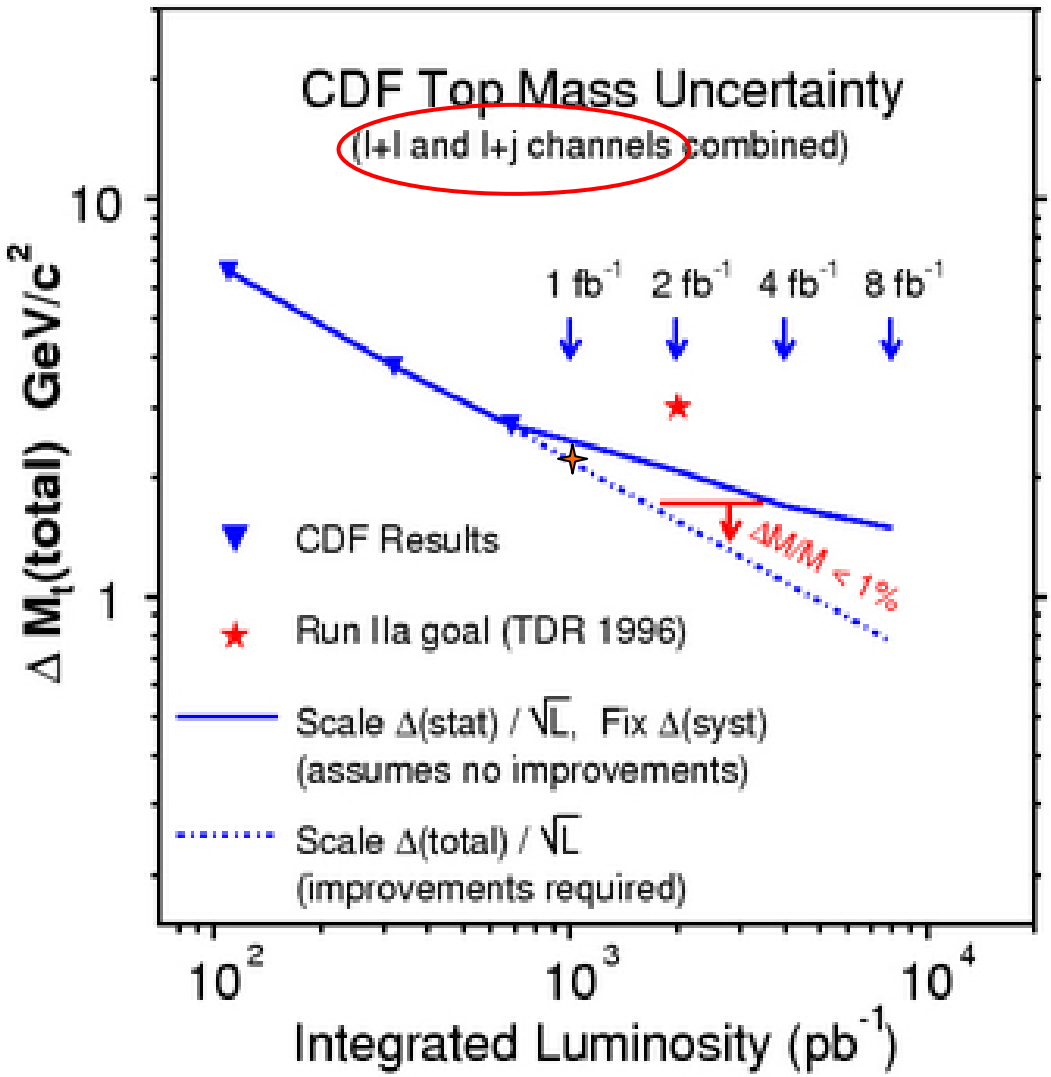
- Use of b-JES from Z→bb sample
- New b-jet taggers
- Improvements in jet E resolution
- New ideas, new samples

CDF with >4/fb promises to reach below 1% alone, and CDF+D0 together may get to σ_m ***= 1.0-1.2 GeV.***

From top mass alone we will not learn much more within the SM. However,

→ the top mass is critical for BSM model building

→ will be a legacy to LHC for the ***calibration of the jet E scale*** *of the Atlas and CMS detectors*

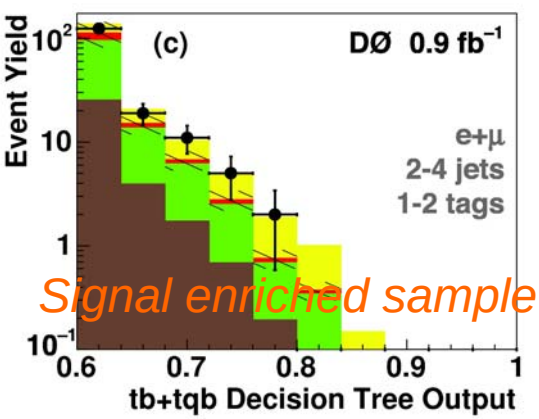


Evidence for single top production

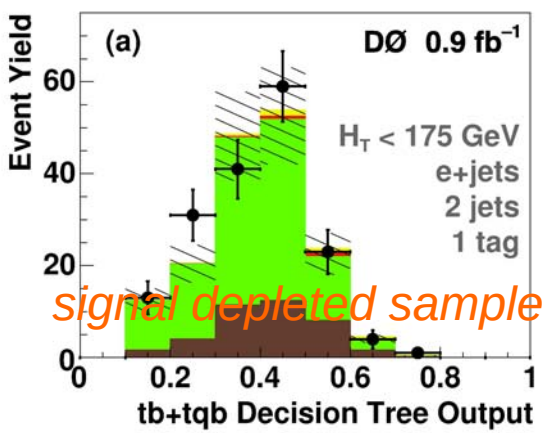
D0 searched for electroweak production of top quark with three methods: decision trees (DT), matrix element (ME), and a neural network (NN).
The signal is elusive: small and easy to mock by backgrounds (W+jets, tt).
Discriminants are constructed with a large number of kinematic observables (DT, NN) or by evaluating the differential probability of signal with single top ME.

Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

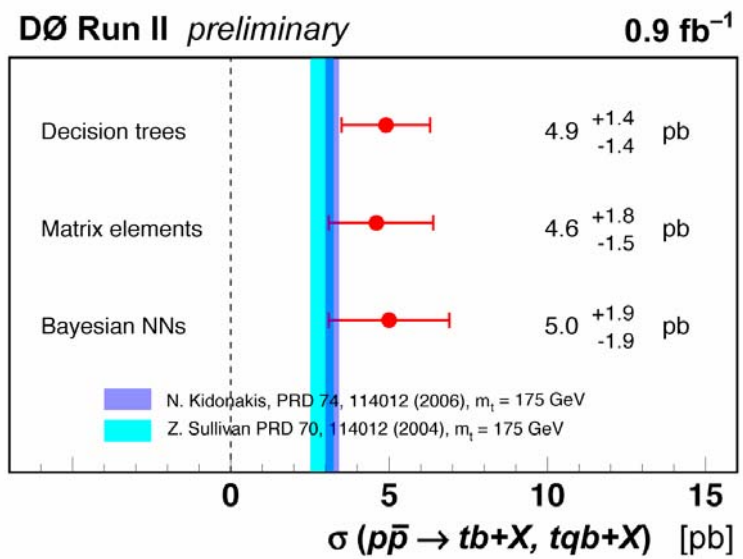
A product over all bins (N_{jets}, N_{tags}, lepton type) of the discriminant outputs is fit with a likelihood. This results in a ***up to 3.4σ evidence*** *(DT) of signal.*



Signal enriched sample

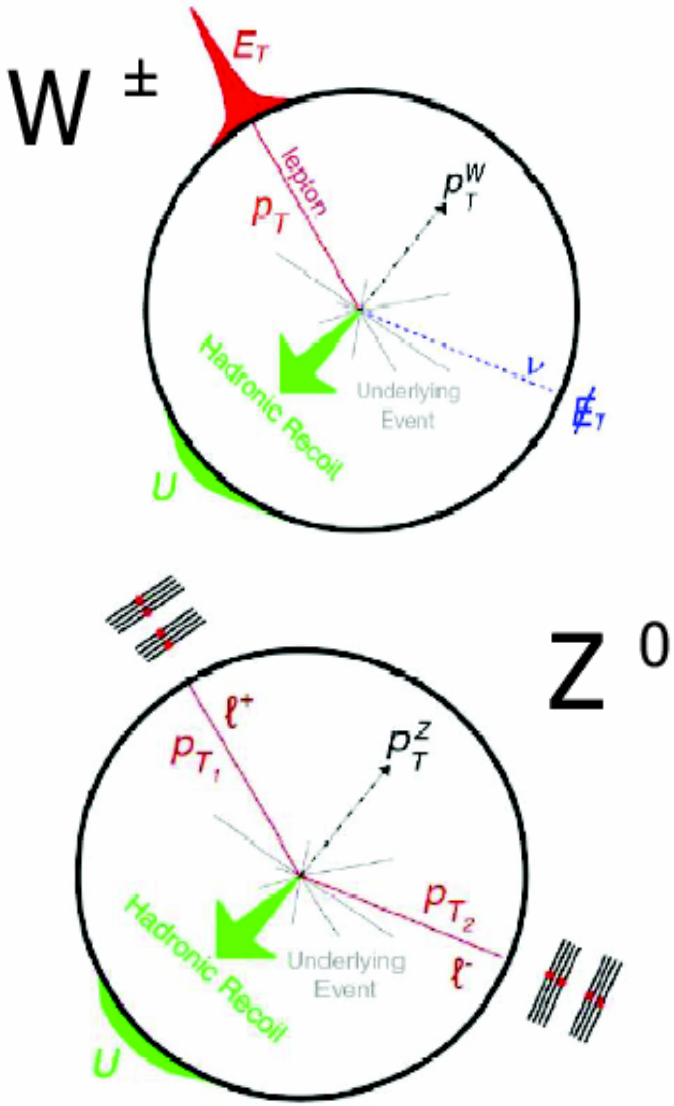


signal depleted sample



Electroweak Physics

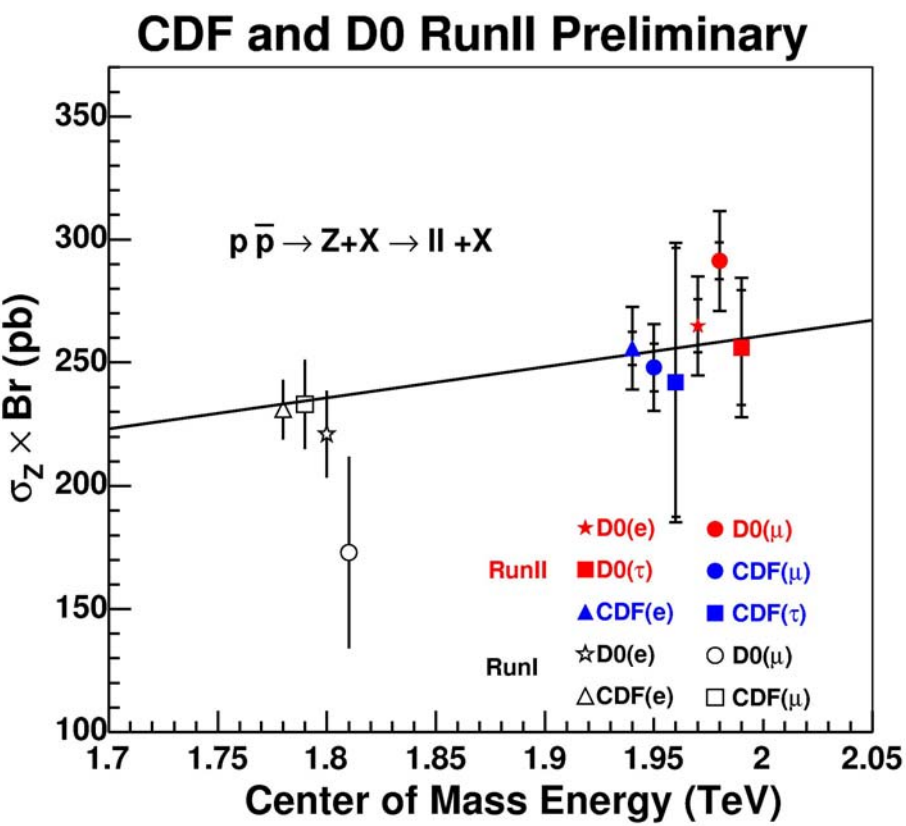
- At the Tevatron, W and Z bosons are produced by quark-antiquark annihilation
- CDF and D0 are using the millions of W and Z boson decays collected in high-P_t lepton samples to produce excellent measurements of electroweak observables
- EW bosons are also fundamental tools for calibrations and checks:
  - EM energy scale
  - momentum scale in tracker
  - resolution in missing transverse energy
  - calorimeter response to low E_t hadronic activity (boson recoil)
  - input to PDF at low x from W charge asymmetry measurements

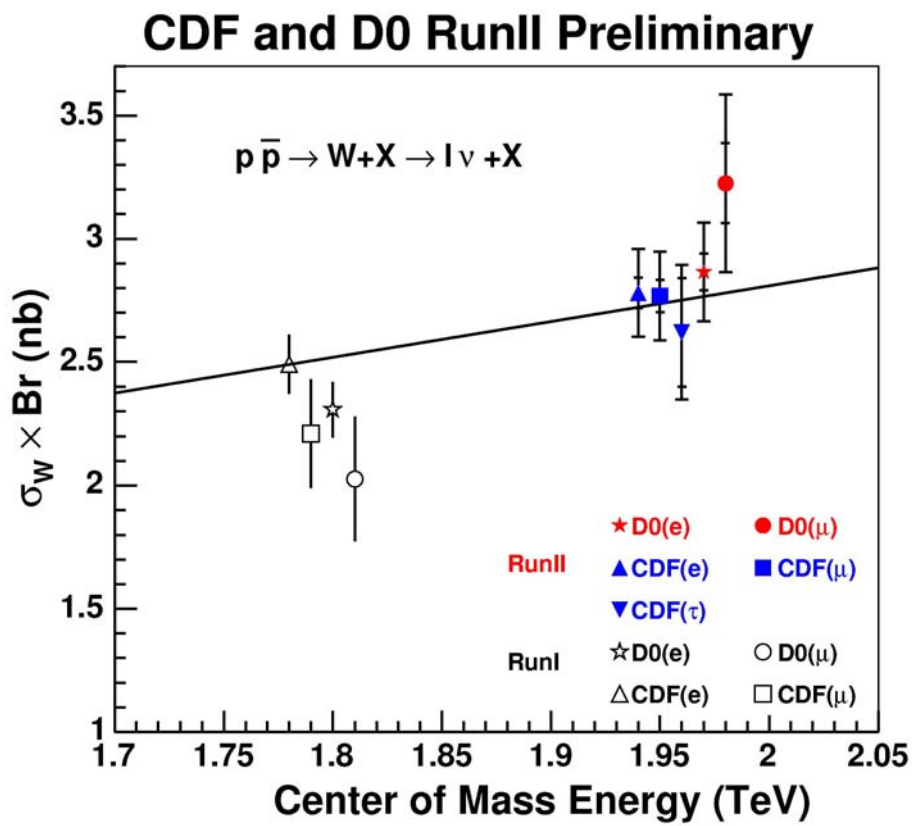


W and Z cross sections

The cross section for inclusive W and Z boson production has been measured in all leptonic final states ***(W→ e****ν, μν, τν;* ***Z→ ee****, μμ, ττ****)*** *by CDF and D0*

- *Results agree well with theory predictions (NNLO, 2% uncertainty – Stirling, Van Neerven)*
- *The experimental uncertainty is by now dominated by luminosity error (6%)*

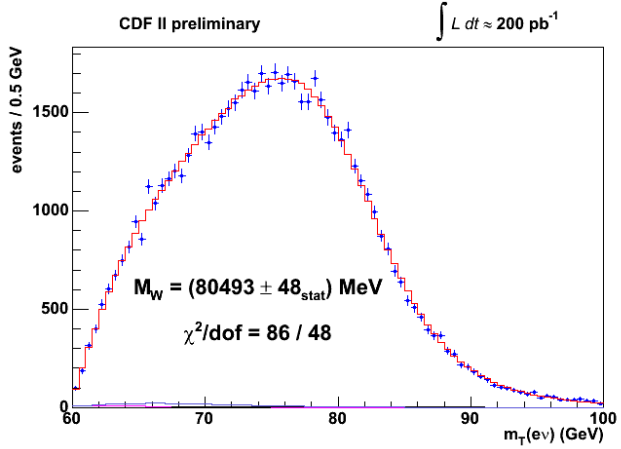


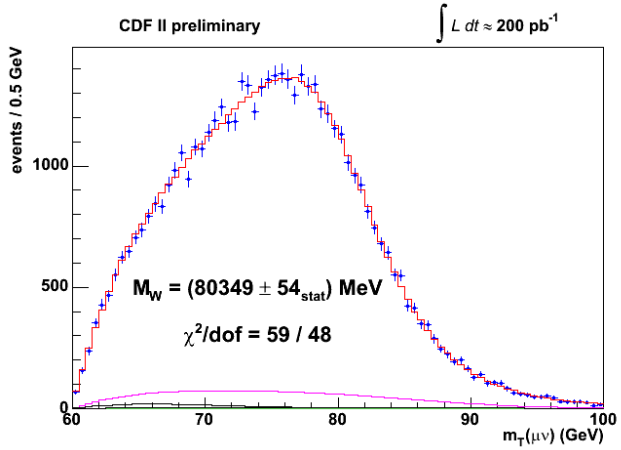


Measurement of M(W)

The W mass is measured by CDF in high-P_t e, μ samples

- select $E_t(P_t)$>30 GeV and missing E_t>30 GeV
- perform transverse ($l\nu$) mass fits after a careful modeling of lepton energy scale & resolution, backgrounds, hadronic recoil



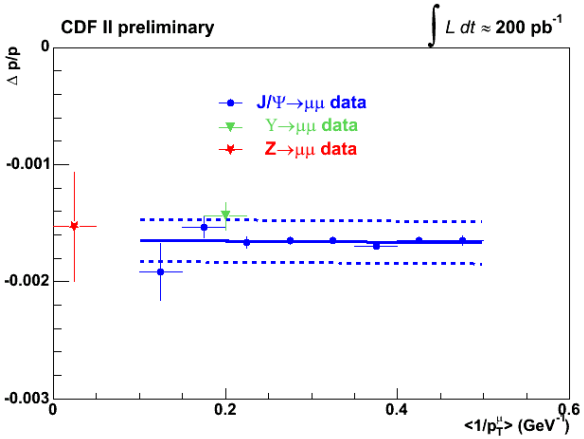


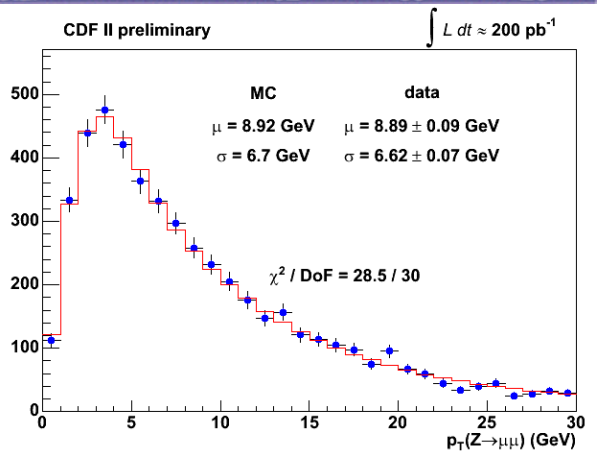
With 200/pb CDF finds:

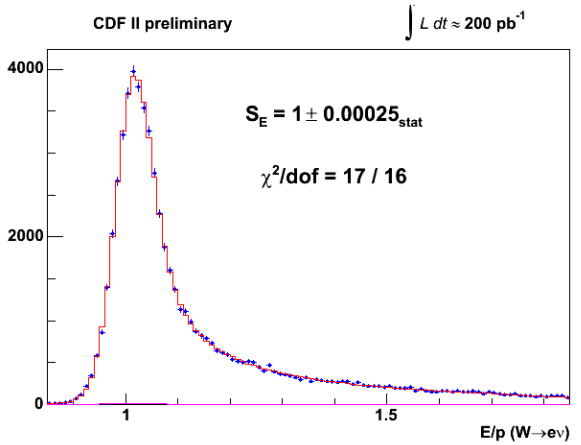
M(W) = 80413 ± 48 MeV

CDF II preliminary — L = 200 pb^{-1}

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26



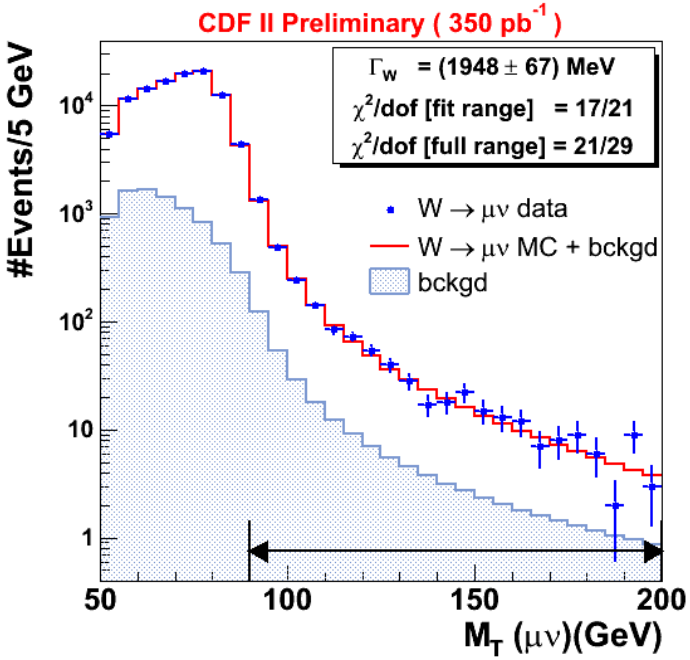




Direct measurement of Γ_W

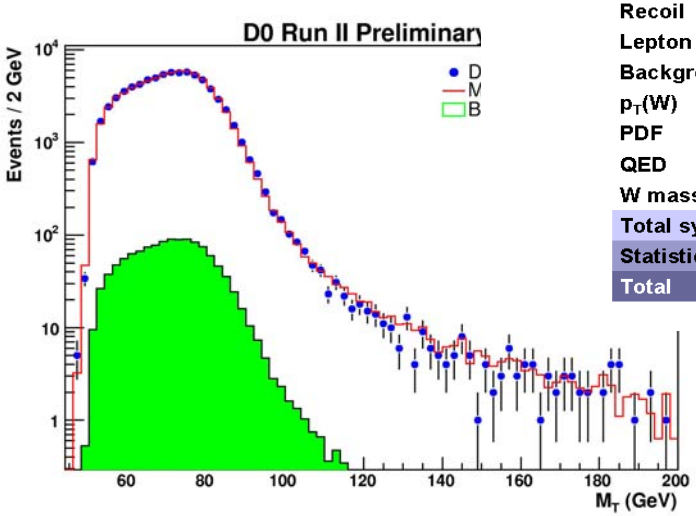
- A direct measurement of the width of the W boson can be obtained with events off mass-shell, where resolution effects in M_W are small
- The analysis shares many systematics with W mass one. Main additional complication is the shape of high-mass QCD background.

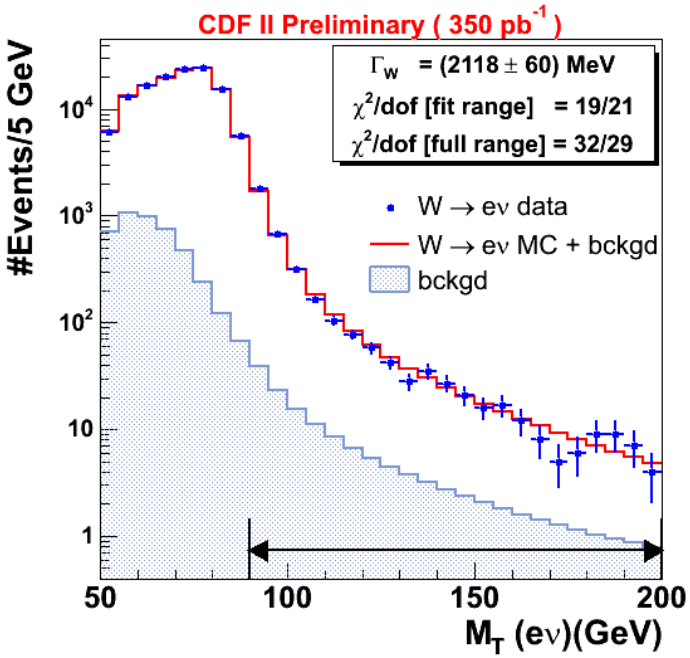
→ With 177/pb (e) D0 finds Γ_W **= 2011 ± 142 MeV**;
→ With 350/pb (e,μ) CDF finds Γ_W **= 2032 ± 71 MeV**



CDF Run II Preliminary (350 pb^{-1})

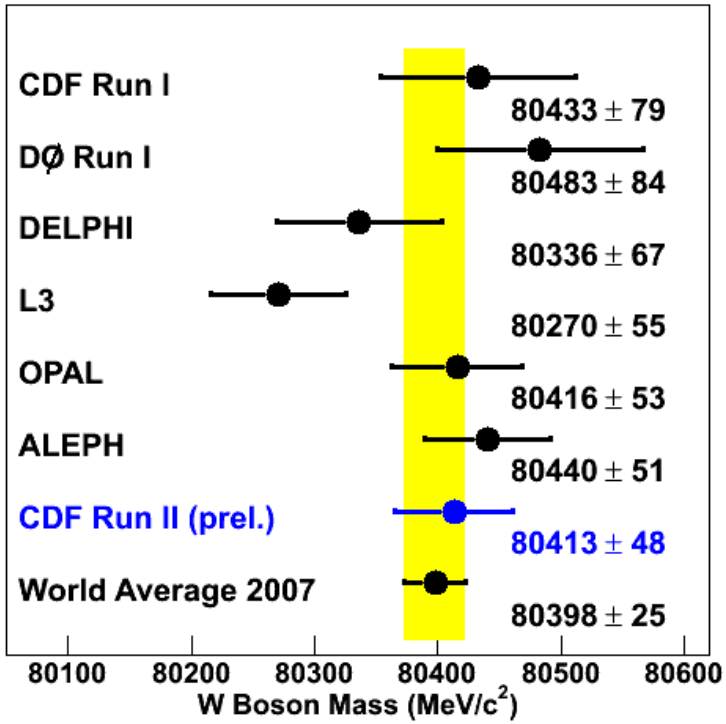
	$\Delta\Gamma_W$ [MeV]		
	Electrons	Muons	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	0
Simulation	13	0	0
Recoil	54	49	0
Lepton ID	10	7	0
Backgrounds	32	33	0
p_T(W)	7	7	7
PDF	16	17	16
QED	8	1	1
W mass	9	9	9
Total systematic	78	70	23
Statistical	60	67	0
Total	98	97	23

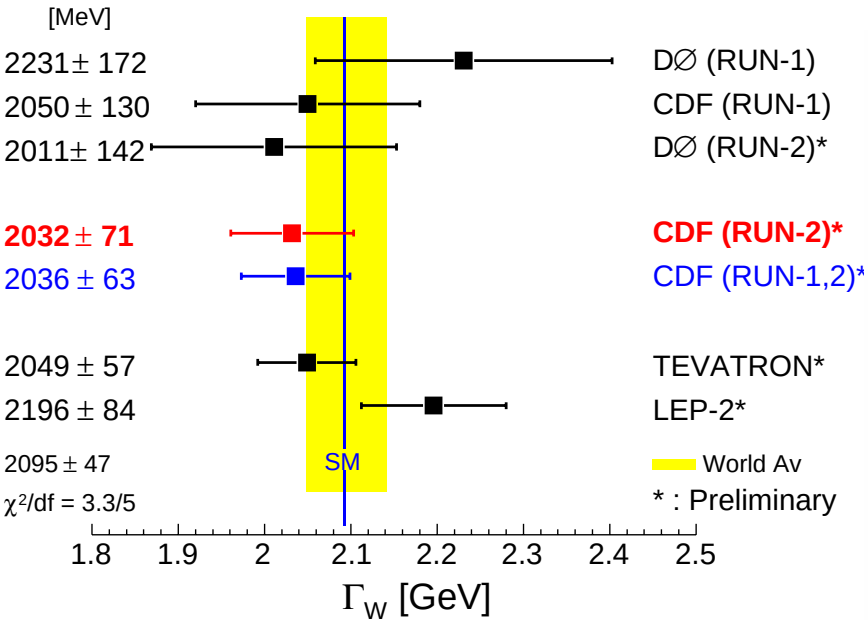


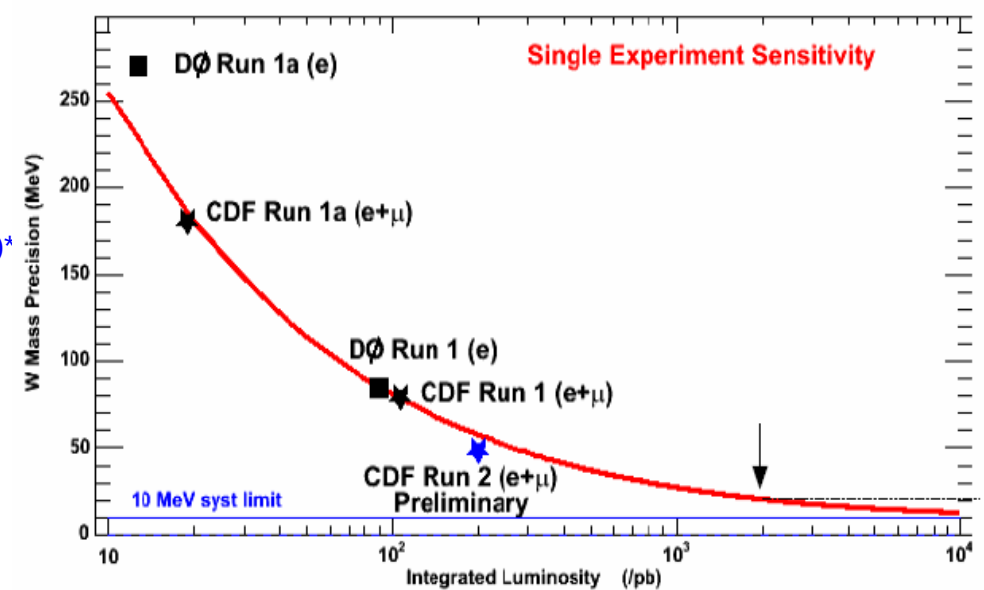


Summary for M_W and Γ_W and prospects

- The Tevatron has now the best measurement of the width of the W boson, and will soon surpass the combined precision of the four LEP II experiments on the W mass
- The agreement with SM predictions for Γ_W is excellent
- By the end of Run II, the W boson mass will be known with close to 0.02% precision!



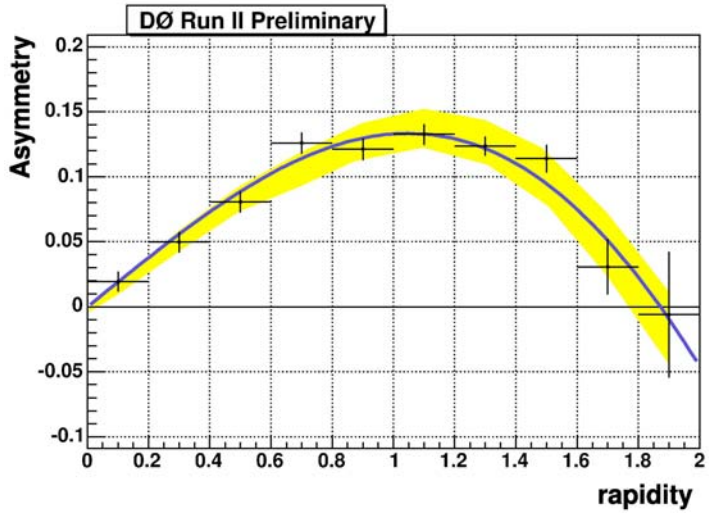




W asymmetry measurements

W bosons exhibit a production asymmetry due to the different PDF of u and d quarks in the proton

$$A(y_W) = \frac{d\sigma_+ / dy_W - d\sigma_- / dy_W}{d\sigma_+ / dy_W + d\sigma_- / dy_W} \approx \frac{u(x1)d(x2) - d(x1)u(x2)}{u(x1)d(x2) + d(x1)u(x2)}$$

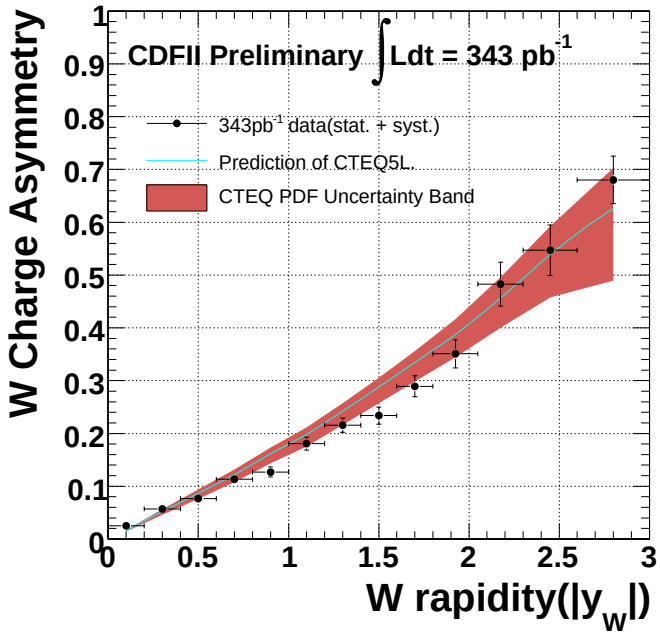


The W rapidity cannot be directly determined →

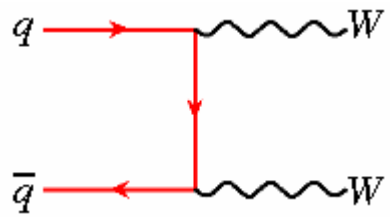
we measure the rapidity asymmetry of charged leptons, which receives an additional contribution from V-A coupling

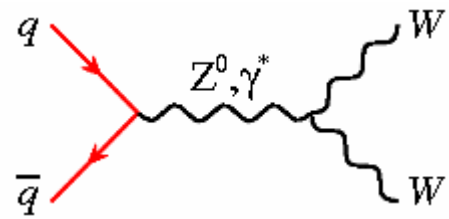
The measured distribution is a stringent test of the d/u PDF at small to intermediate x

Good agreement is found by D0 and CDF with MRST02 (top) and CTEQ5L (bottom) PDF



WW production





Mode	ll
WW	$52.4 \pm 0.1 \pm 4.3$
Drell-Yan	$11.8 \pm 0.8 \pm 3.1$
W+jets	$11.0 \pm 0.5 \pm 3.2$
$WZ+ZZ$	$7.9 \pm 0.0 \pm 0.8$
$W\gamma$	$6.8 \pm 0.2 \pm 1.4$
$t\bar{t}$	$0.2 \pm 0.0 \pm 0.0$
Sum Bkg	$37.8 \pm 0.9 \pm 4.7$
Expected	$90.2 \pm 0.9 \pm 6.4$
Data	95

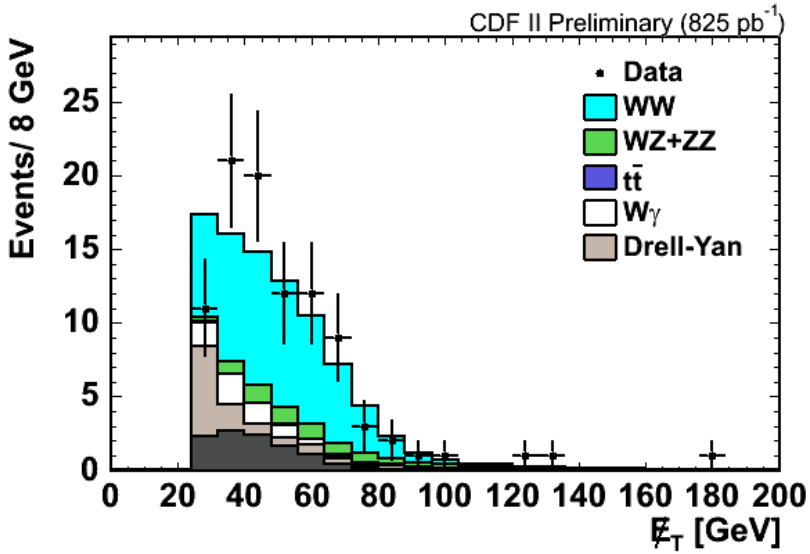
Both CDF and D0 have by now sizable (= O(100 evts)) samples of WW events

- These provide insight into main backgrounds to Higgs boson searches at large M(h)
- Clean EW process, test trilinear couplings

Most recent result: CDF, 825/pb of data

- Cross section in good agreement with NLO theory +CTEQ6 PDF [σ=12.4±0.8 pb: J.Campbell, R.Ellis, PRD 60 (1999)113006]:

$$\sigma = 13.6 \pm 2.3(stat) \pm 1.6(sys) \pm 1.2(lum)\ pb$$



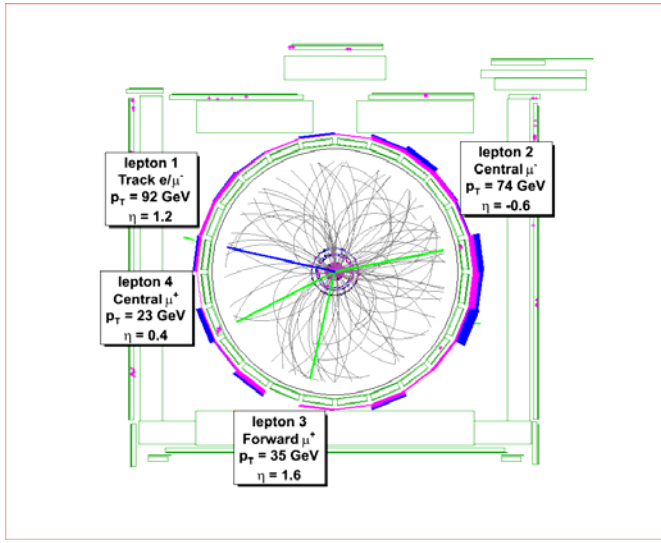
CDF: WZ and ZZ production

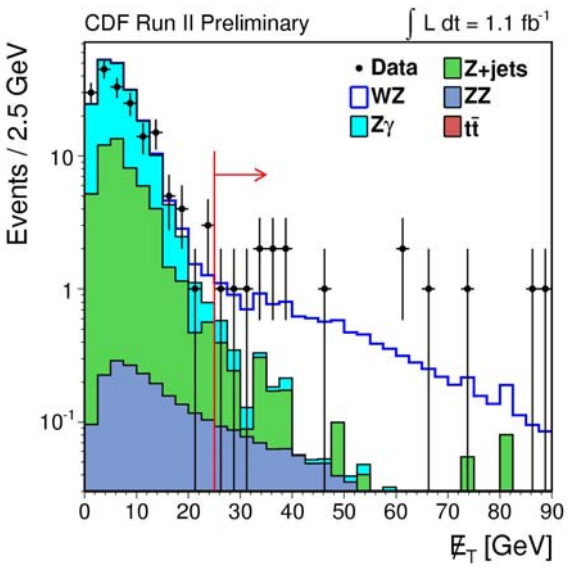
The process pp→WZ→lllν is easily separable from the sparse EW backgrounds

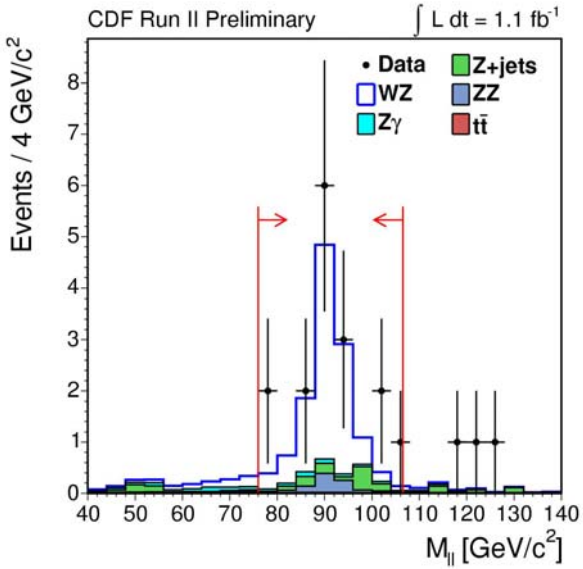
- CDF finds 16 candidates, expects 2.7±0.4 from backgrounds
- a **6-sigma signal.**
- Result: **σ(WZ) = 5.0+1.8-1.6 pb** (NLO: 3.7±0.3 pb)

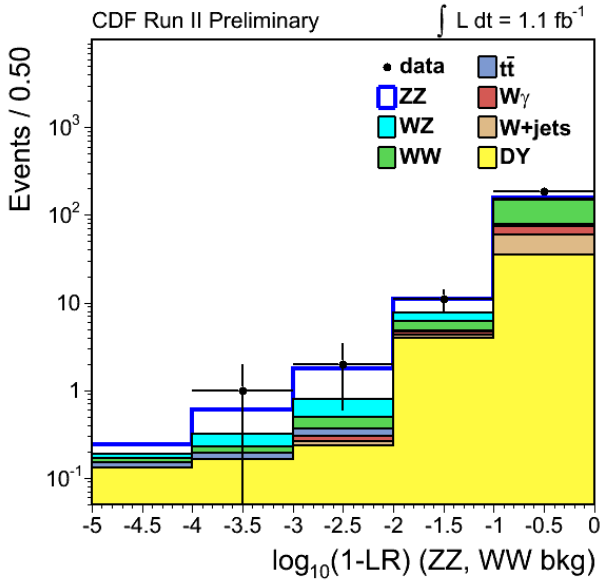
The process pp→ZZ is sought after in final states with 4 charged leptons or 2 leptons plus missing energy

- Dominant backgrounds: Drell-Yan production, WW
- CDF extracts an excess on the tail of the log-likelihood ratio of signal and background.
- The result is **σ(ZZ) = $0.75^{+0.71}_{-0.54}$ pb**, a **3-sigma signal** again in good agreement with NLO theory.







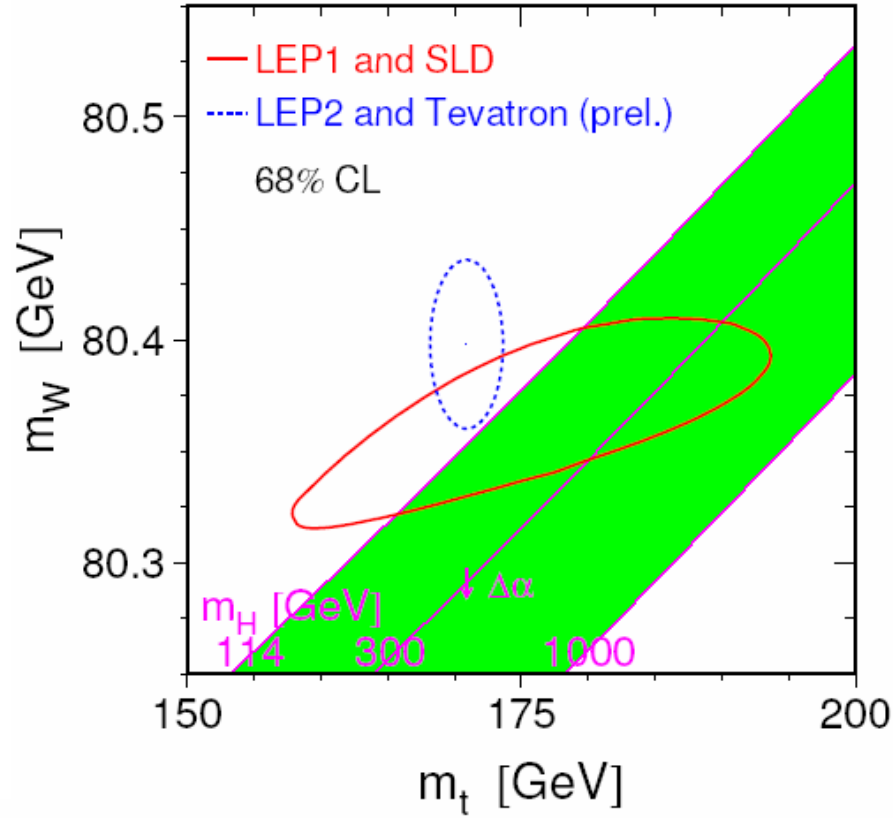


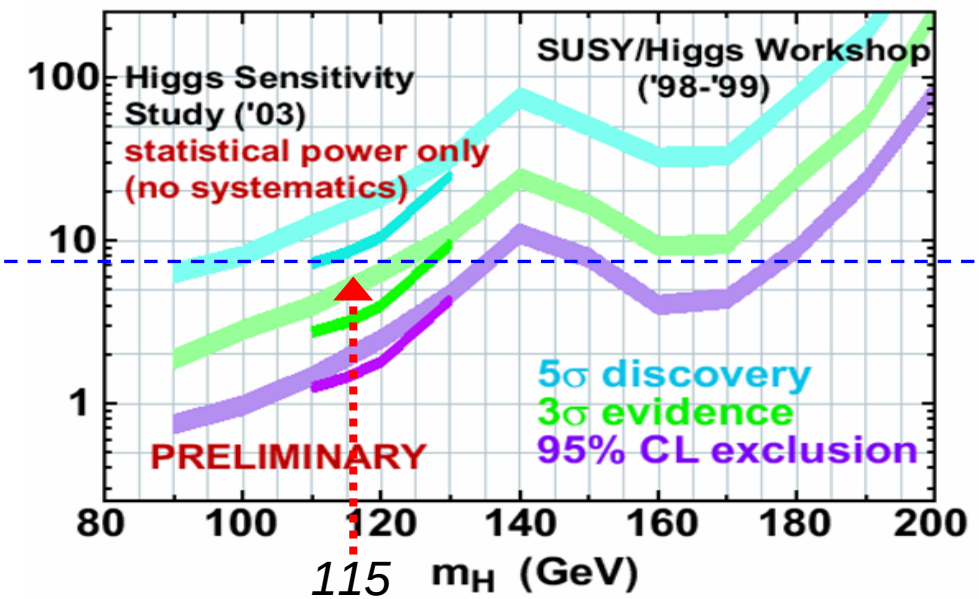
Putting things together…

The recent improvements in top and W mass determinations push the most likely value of the Higgs boson mass deep down into the excluded region

- Global fits to SM observables indicate **$M(h) = 76^{+33}_{-24}$ GeV**
- The $\Delta(\chi^2)$ curves start to erode the higher mass region:
  M(h)<144 GeV @ 95%CL
- The above bound favors the Tevatron and disfavors LHC
- The other view: taking the LEP bound into account, **M(h) < 182 GeV at 95%CL**
  → any scenario is still open

When ends don't meet, one pulls out the magnifying lens… Let us have a look at the inputs

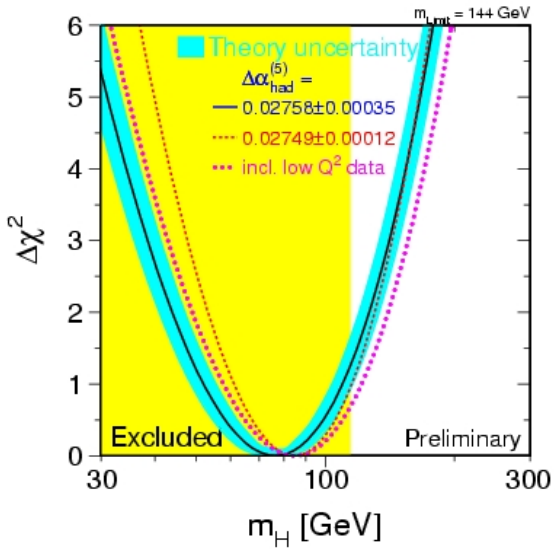


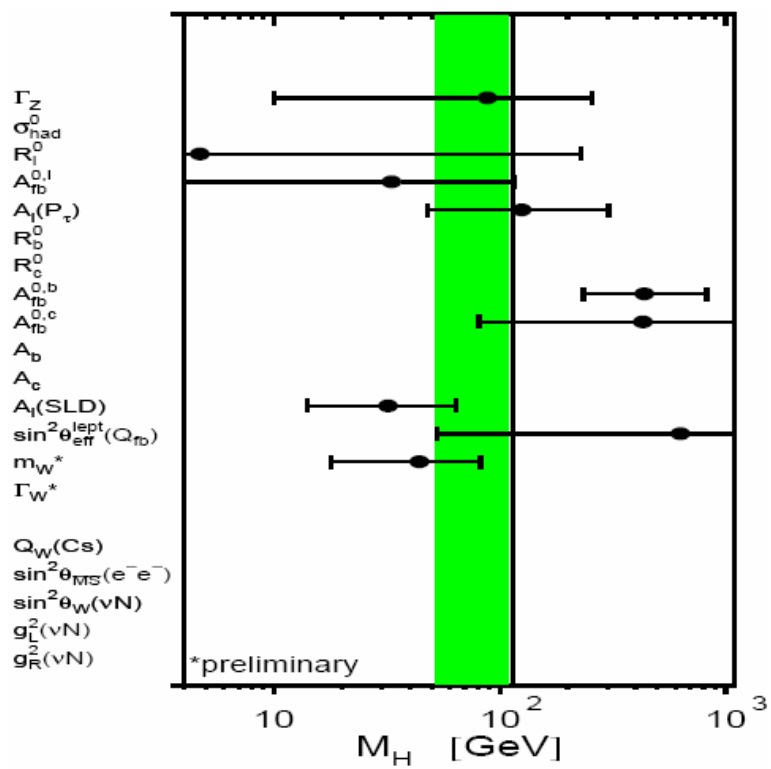


More about global fits

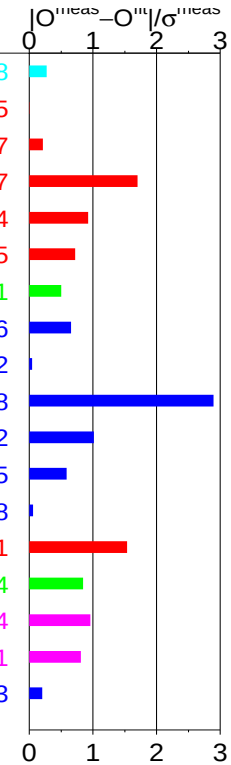
Some observables are more responsible than others in pulling the average expected Higgs mass down

- Strongest pull downward comes from A(l) at SLD and the W mass results
- The usually excluded low-Q^2 data do not make much difference any more
- If it weren't for $A(fb)_b$ the tension would be much stronger
- **Everything still goes, but the margin is narrowing**…





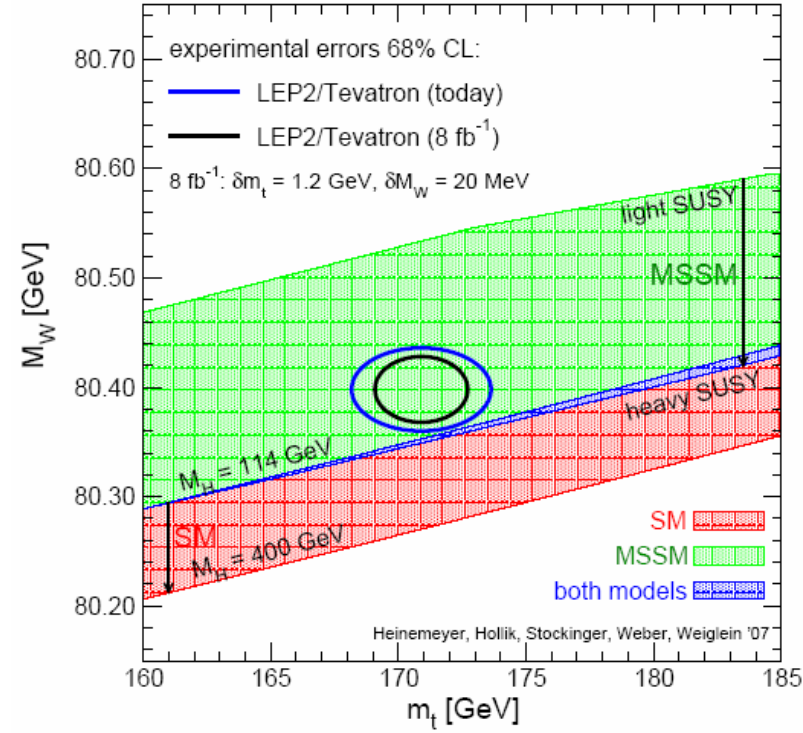
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

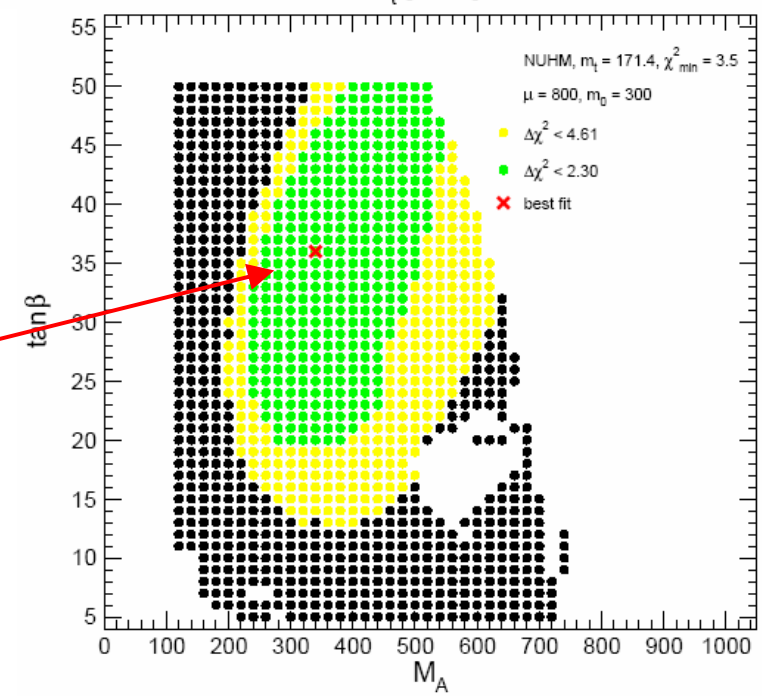


And what if…

- The SM is a overwhelmingly successful theory, but we know it is not enough
  - With the precision of masses and other observables increasing, the mountain of evidence could start to crumble under its own weight as soon as the Tevatron manages to push up the lower limits on M(h) by direct searches

- In the context of MSSM models things still look quite good for a wide chunk of the parameter space of some benchmark scenarios
  - Within the NUHM (non-universal Higgs model) one can fit well also B-physics and dark matter constraints to the lightest SUSY particle from WMAP together and obtain a coherent picture
  - By scanning the parameter space in a way that keeps DM constraints satisfied, one can construct "WMAP surfaces" and determine preferred regions in the standard M(A) vs tan(β) plane
- See recent paper by S.Heinemeyer et al. (Hep-ph/07060652) for more details and discussion





CONCLUSIONS

The Tevatron experiments are producing exquisite new results in high-Pt physics, and are bringing the tests of the Standard Model at a level of precision which meets or exceeds that of electron-positron colliders

- The top mass is known with **1% precision**, the W mass with **0.04% precision**
- These results are bringing the consistency tests based on radiative EW corrections close to the breaking point

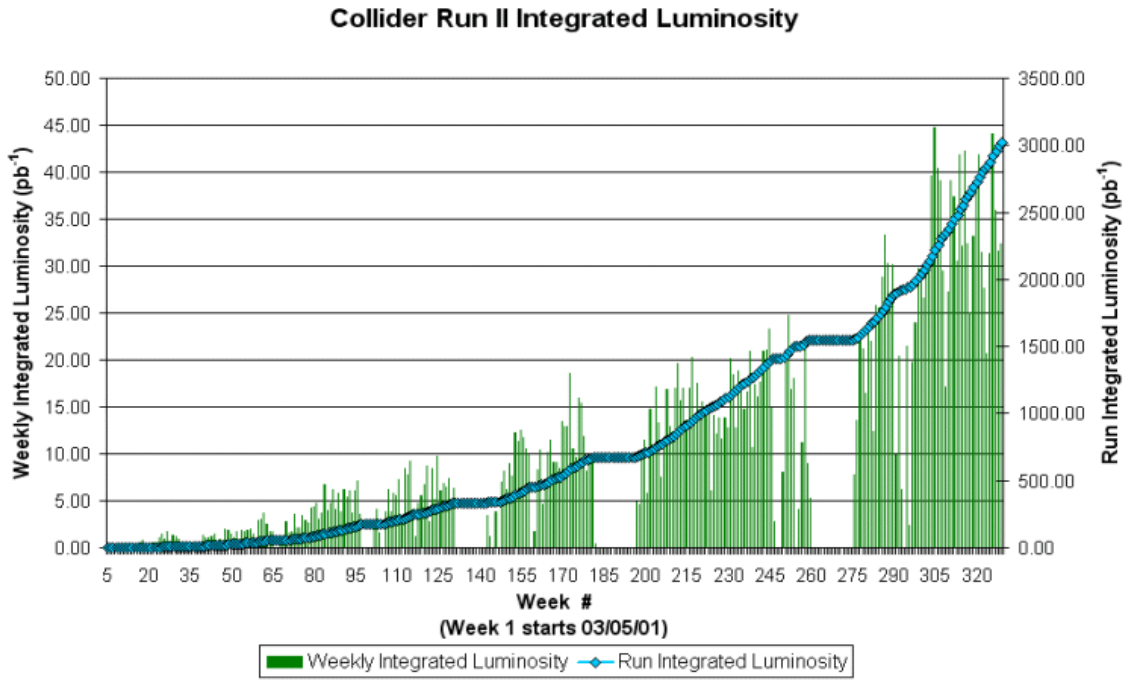
The CDF and D0 experiments will continue to produce excellent physics through 2009, and possibly after that

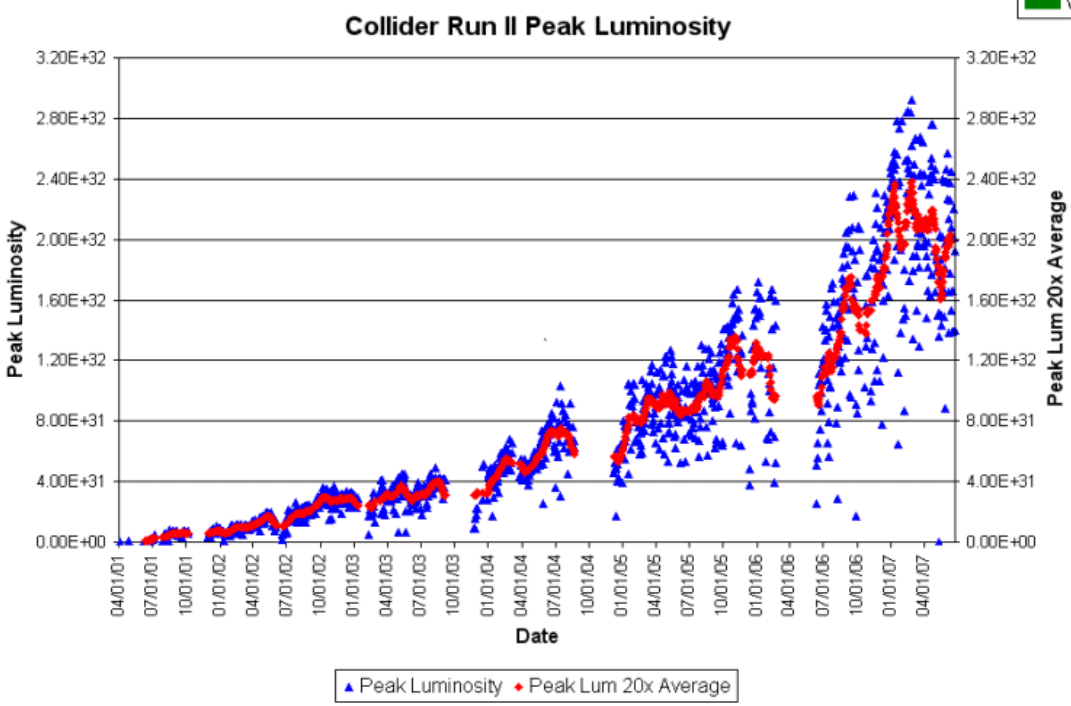
- *Expect 0.7% precision on top mass, 0.02% on W mass*
- The Higgs boson hunt is under way
- Surprises may be just around the corner
- See G.Sajot's and V.Buescher's talks for news on Higgs & BSM searches

The Standard Model may not be the final theory of particle physics, but it insists in explaining our data well after 30 years of investigations

BACKUP SLIDES

Luminosity plots





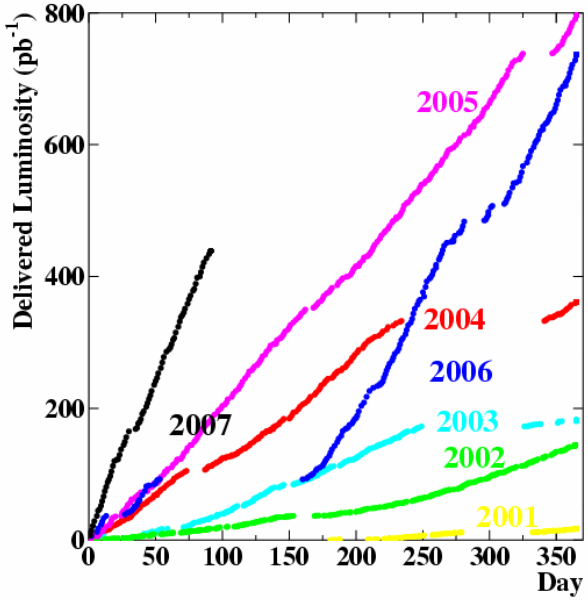
Current records:

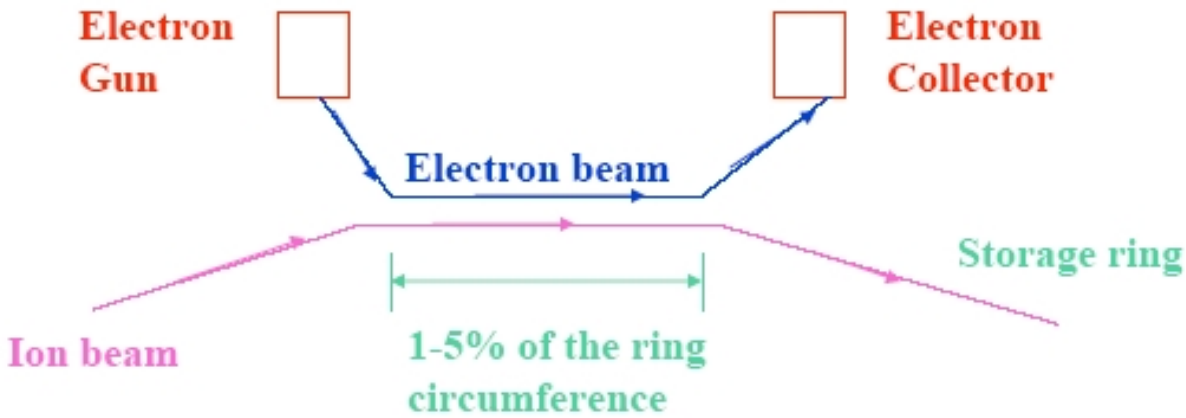
43/pb/w,

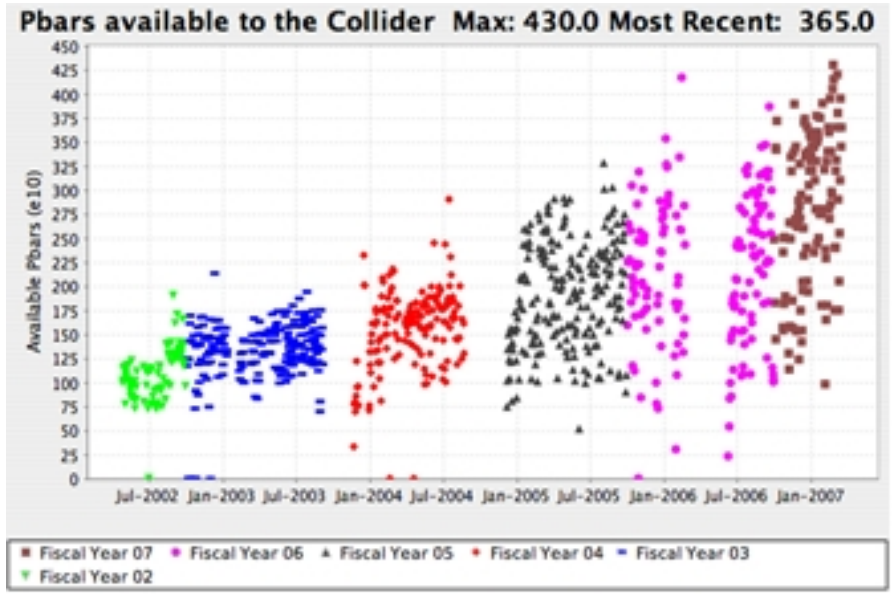
162/pb/mo,

L = 2.92 E32 cm^{-2} s^{-1}

BKP - Upgrades at Tevatron

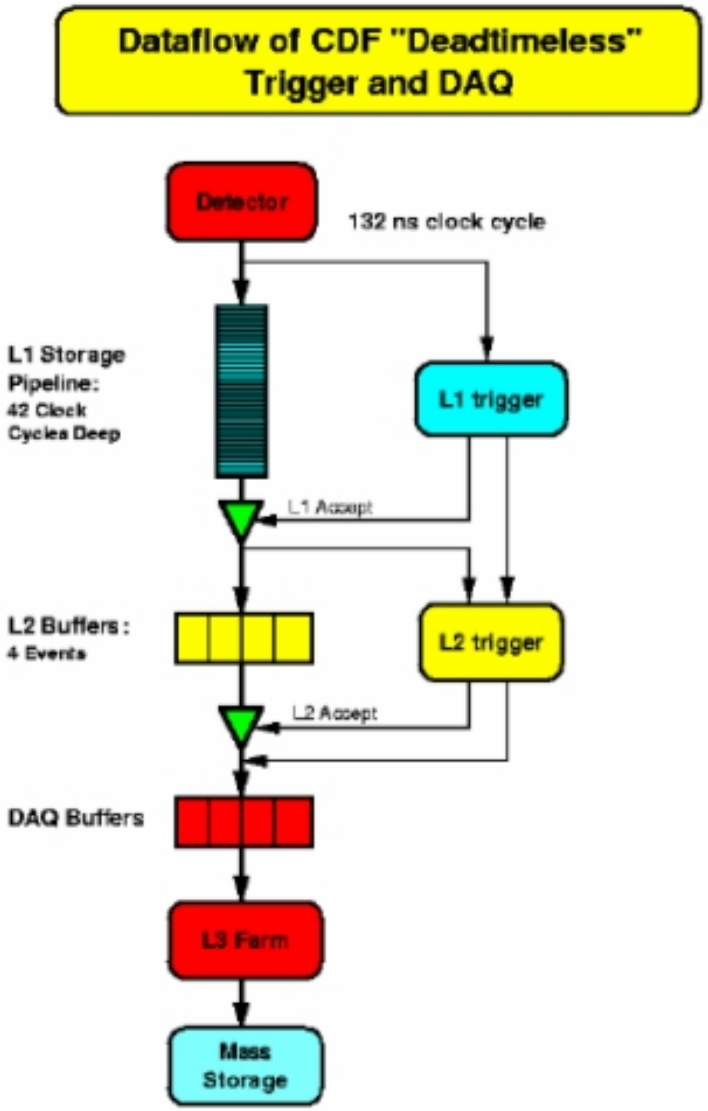






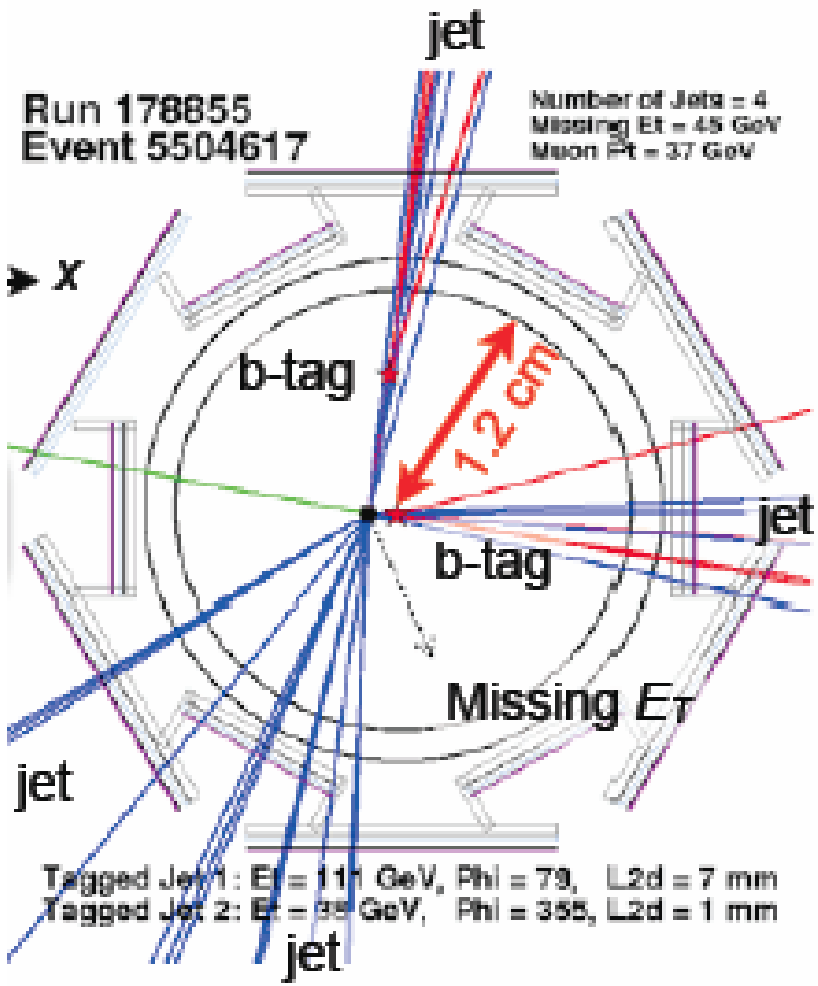
CDF Trigger system

- The trigger is organized in 3 levels
  - L1: hardware, synchronous
    - processing in parallel
    - Pipeline 42 clock cycles deep
    - decision in 5μs
    - Accept rate max 35 kHz
  - L2: hardware and software, asynchronous
    - Average decision time 30 μs
    - Accept rate max 600 Hz
  - L3: software
    - Farm of PC
    - Speed-optimized offline algorithms
    - Accept rate max 100 Hz



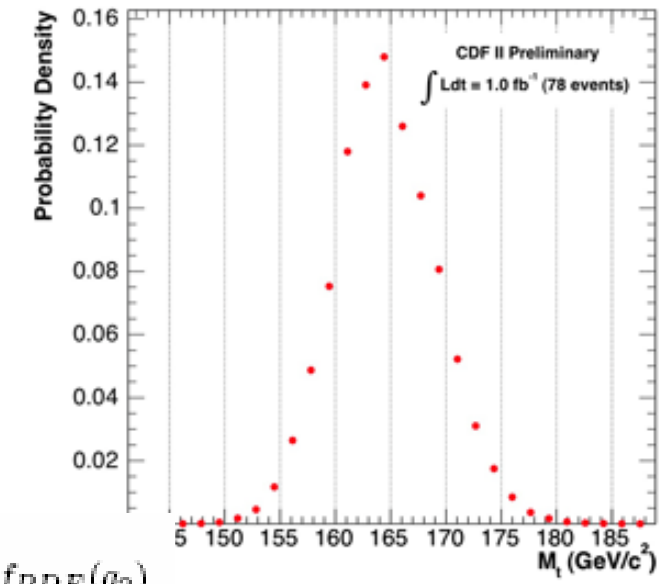
Top Quark Physics: b-tagging

- The silicon vertex detectors in CDF and D0 allow the reconstruction of the decay path of B hadrons produced by b-jet fragmentation
- Typical IP resolutions: 15 μm
- Typical b-tagging efficiency on top decay b-jets: 50%; fake rate: 1%.
- B-jets are fundamental tools for many high-Pt analyses besides top physics
  - Higgs searches at low M(h)
  - QCD measurements
  - SUSY searches



The three most precise top mass determinations – 1: Dilepton channel

The cleanest decay channel provided CDF with 78 events in 1/fb (50±2 from top pairs)



Use is made of a global event likelihood as a function of M_{top} uby integrating on phase space with a weight from (parton→jet) transfer functions and LO matrix element for top pair production

$$P(\mathbf{x}|M_t) = \frac{1}{N}\int d\Phi_8 |\mathcal{M}_{t\bar{t}}(p;M_t)|^2 \prod_{jets} W(p,j)W(p_T,U)f_{PDF}(q_1)f_{PDF}(q_2)$$

Backgrounds (DY, WW, W+jets) are dealt with in the same way, using their relative probability:

$$P(\mathbf{x}|M_t) = P_s(\mathbf{x}|M_t)p_s + P_{bg1}(\mathbf{x})p_{bg1} + P_{bg2}(\mathbf{x})p_{bg2}\cdots$$

Result:

M_{top} = 164.5 ± 3.9 (stat.) ± 3.9 (syst.) GeV/c^2

Source	Size (GeV/c^2)
Jet Energy Scale	3.5
Multiple Interactions	0.2
Lepton Energy Scale	0.1
Generator	0.9
Method	0.6
Sample composition uncertainty	0.7
Background MC	0.7
Background modeling	0.2
FSR modeling	0.3
ISR modeling	0.3
PDFs	0.8
Total	3.9

3: All-hadronic channel

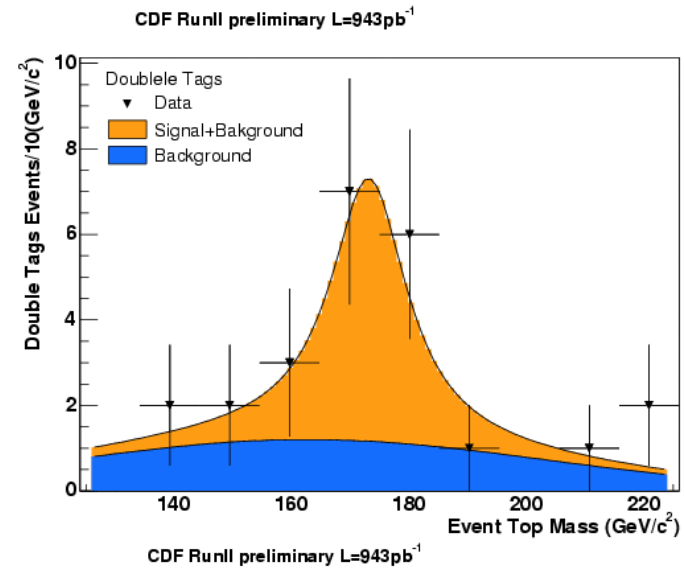
Number of events	1tag	2tag
Signal (ttbar)	13.2(3.7)	14.1(3.4)
Background	34.6(7.2)	9.2(4.3)

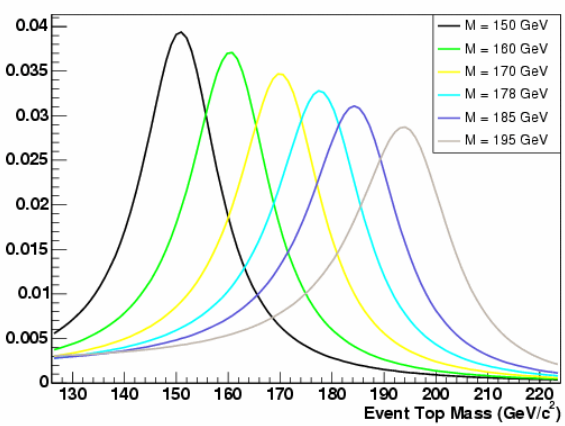
In this channel too the combination of a dynamical likelihood and LO matrix elements allows a precise measurement.

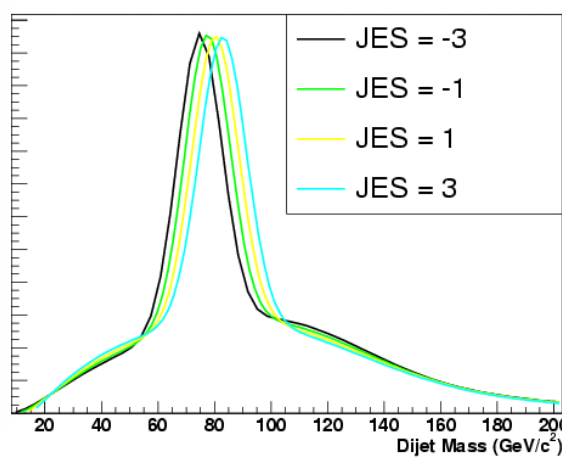
The selection requires 6 jets (E_t>15 GeV, $|\eta|$<2) and uses kinematical cuts now "standard" on aplanarity : ΣE_t^3, centrality C>0.78, ΣE_t>280 GeV, and a cut on the matrix element –based "top likelihood" L<10.

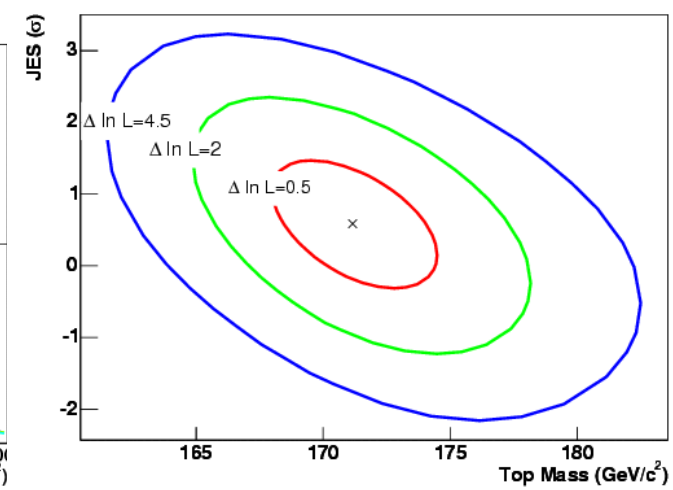
Templates of M_{top} and M_{jj} are then used in a combined fit to M_{top} and the jet energy scale. The result is:

$$M_{top} = 171.1 \pm 3.7\ (\text{stat.+JES}) \pm 2.1\ (\text{syst.})\ \text{GeV}/c^2$$
$$= 171.1 \pm 4.3\ \text{GeV}/c^2$$







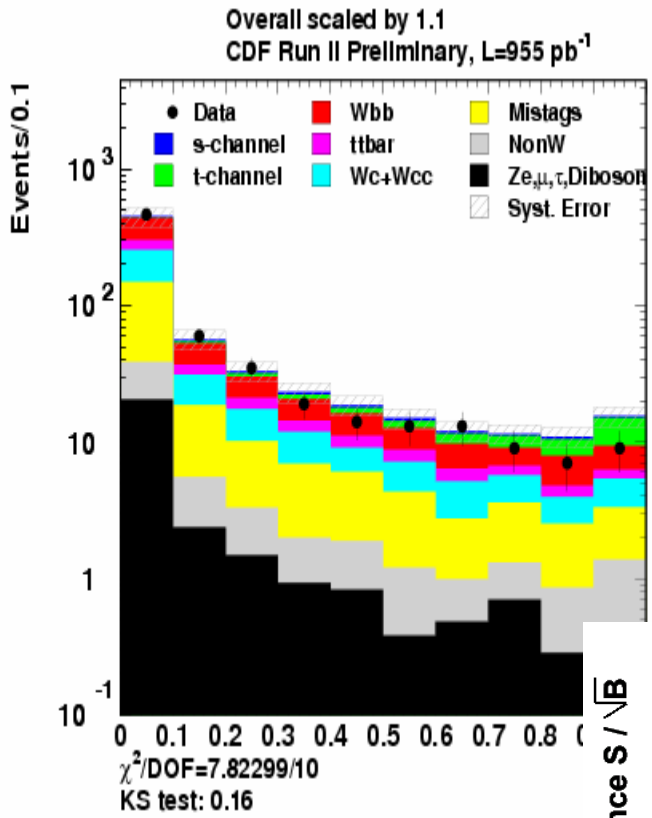


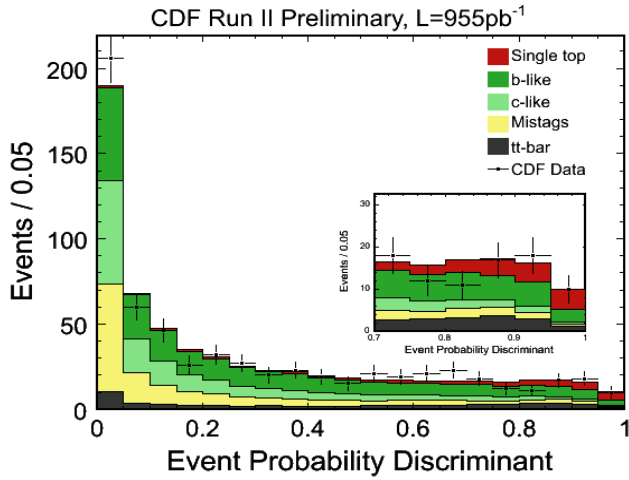
Contradictory results?!

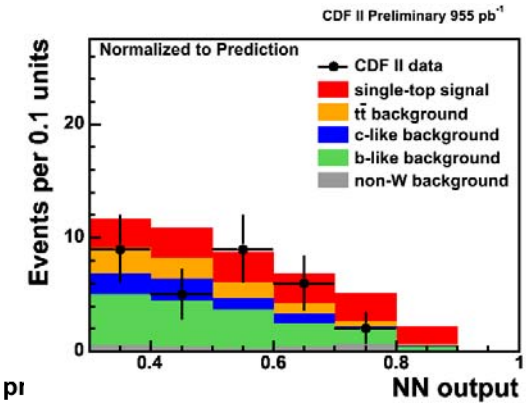
Matrix element:
σ (t-chan.) = 2.7 +1.5 -1.3 pb
Neural Network:
σ (t-chan.) = 0.2 +1.1 -0.2 pb
σ (s-chan.) = 0.7 +1.5 -0.7 pb
2-D Likelihood discriminant:
σ (t-chan.) = 0.2 +0.9 -0.2 pb
σ (s-chan.) = 0.1 +0.7 -0.1 pb
[SM:
σ (t-chan.) = 1.98 pb
σ (s-chan.) = 0.88 pb*]*

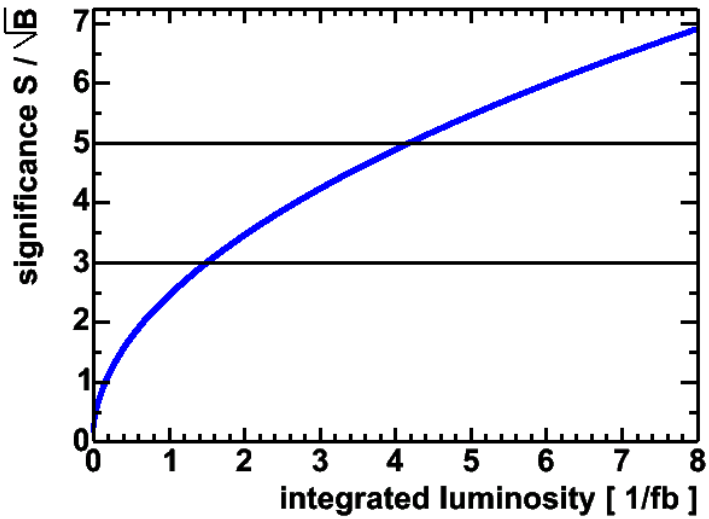
Consistency at 1%

CDF expects to observe at 5σ single top production with 4/fb









Method	Neural Networks		Matrix Elements	Likelihood Function
	1D	2D	1D	2D
Expected p-value	0.5% ≅ 2.6 σ	0.4% ≅ 2.6 σ	0.6% ≅ 2.5 σ	2.5% ≅ 2.0 σ
Observed p-value	54.6%	21.9%	1.0%	58.5%

Miscellanea top physics

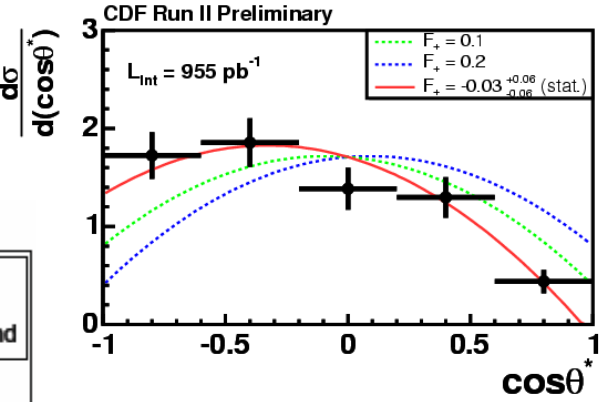
W helicity in top decays: precise results, error still dominated by statistics

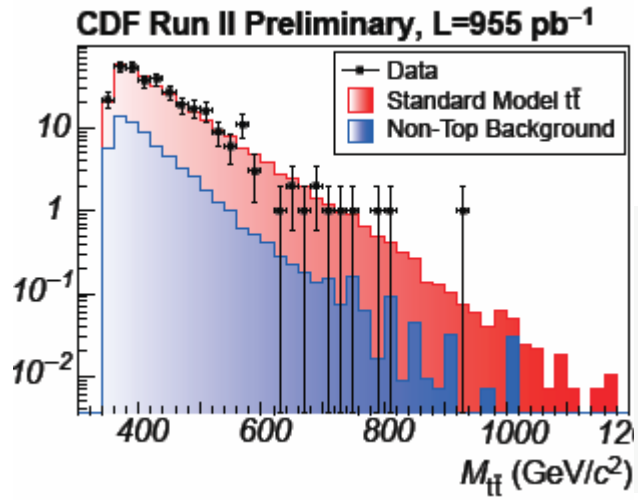
Top pair prod. mechanism: two methods

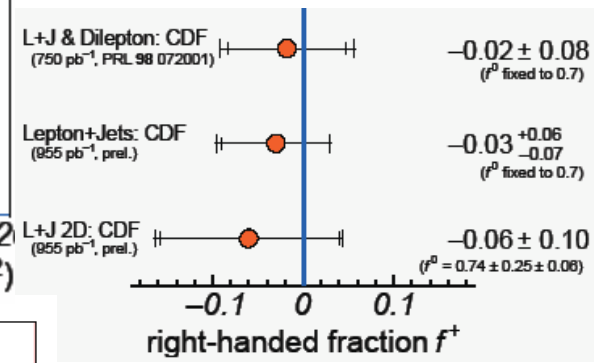
F(gg)=0.01±0.16±0.07

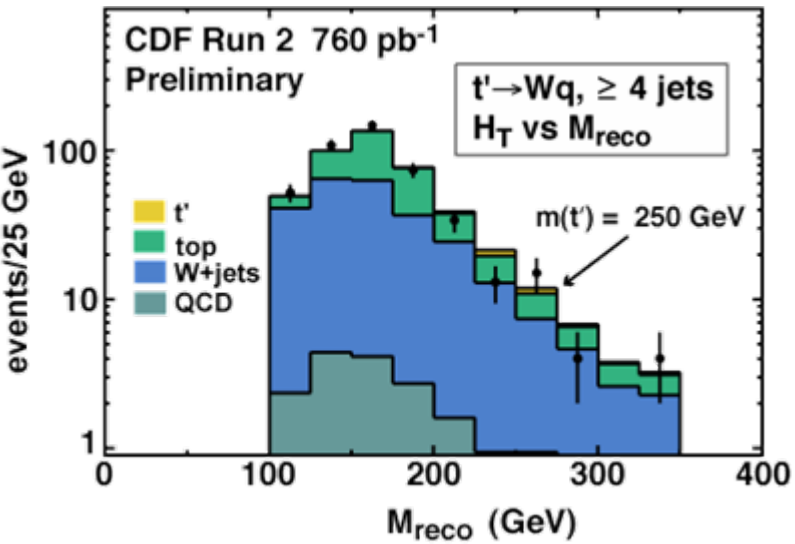
Resonances decaying to top-antitop (Z' leptophobic):

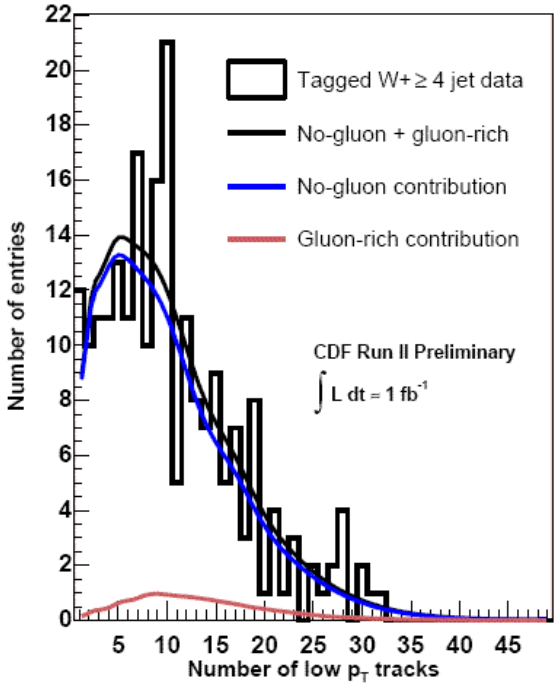
M(Z')>725 GeV @95%CL

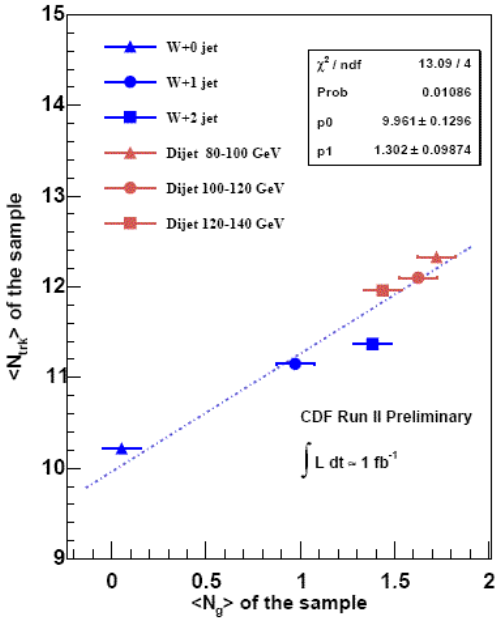












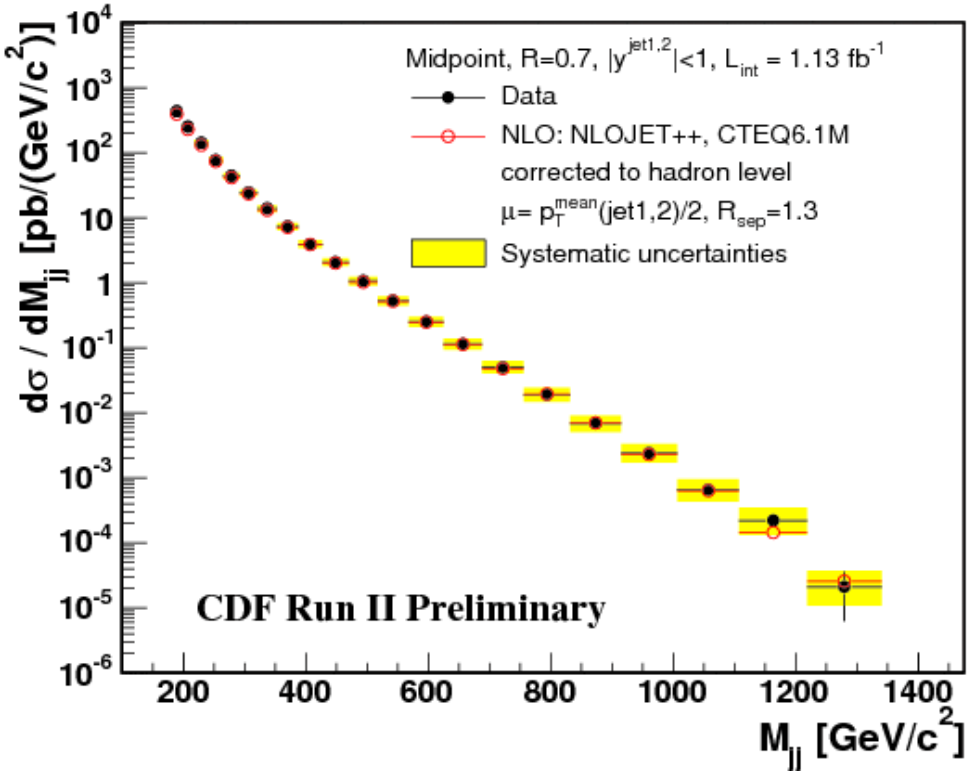
QCD measurements

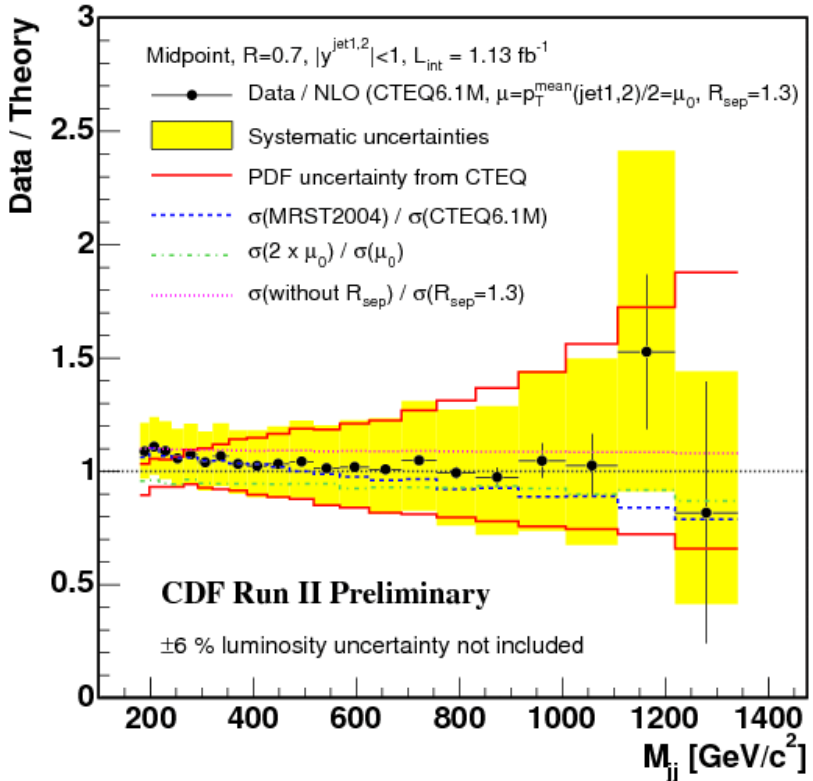
- In the third millennium QCD is not a mystery any more, but there remains to explore regions at the limit of our capabilities – those not yet inserted or tuned in models:
  - **Very high energy** (compositeness, tuning PDF)
  - **Very high molteplicity**, differential distributions (parton showers, tuning of Monte Carlo)
  - **Low x phenomena**, exclusive and diffractive productions, rare processes

- Two examples from recent (1/fb) or innovative results:
  - Dijet mass cross section
  - Exclusive gamma-gamma production (0.54/fb)

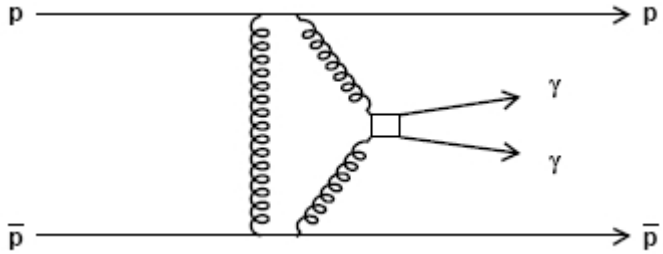
Dijet mass cross section

- Measurement done with 1.13/fb using midpoint algorithm, R=0.7, |y|<1.0
- Cross section spans 8 orders of magnitude
- Great agreement with NLO pQCD if CTEQ6.1M PDF used (r. & f. scales = <Pt/2>) between 200 and 1300 GeV of invariant mass
- Accuracy of the measurement similar to PDF error
- Data used also to obtain limits to strongly coupled resonances

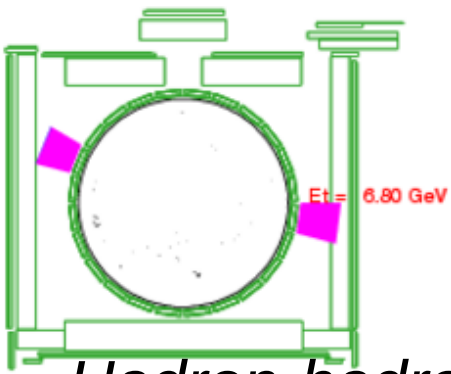


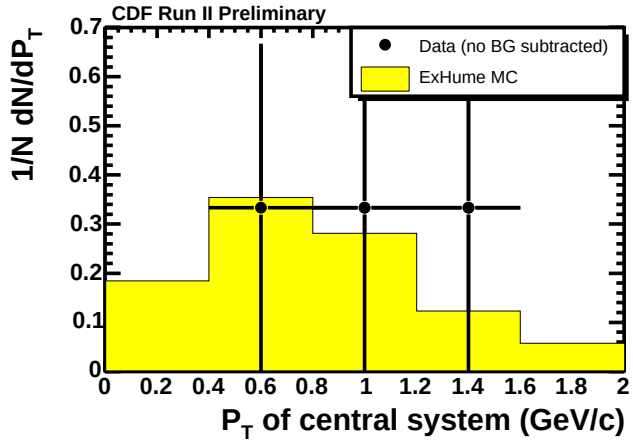


Exclusive production: $\gamma\gamma$

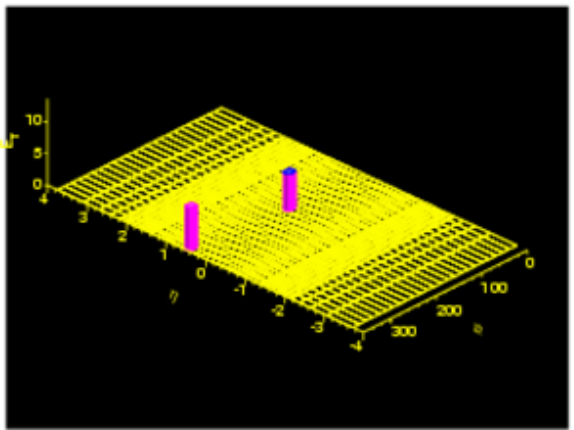


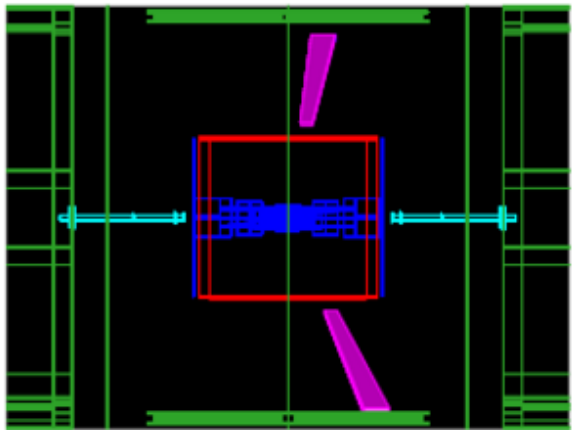
- Quite interesting process to study: no underlying event, "LEP-like" cleanness of detector
- Only ISR produced evidence of exclusive QCD production ($\pi\pi$) in the past
- Important to study exclusive H production at LHC
- L=532/pb collected by CDF with a dedicated trigger (veto BSC $5.4<|\eta|<5.9$)
- **3** events observed, **0±0.2** expected, **σ=0.14+0.14-0.4±0.3pb**, expected σ=0.04 pb with large theoretical uncertainty (Durham group).

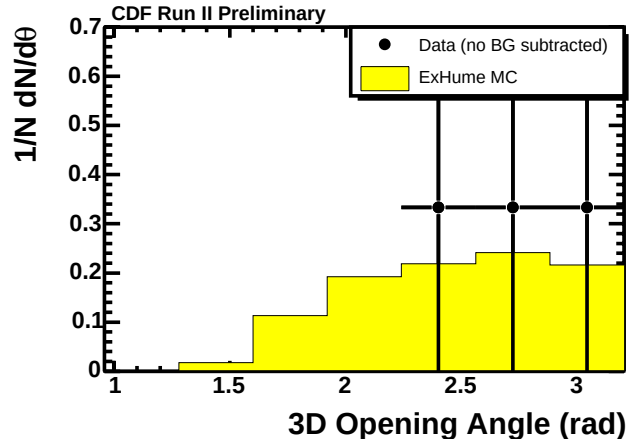




Hadron-hadron collision ??????



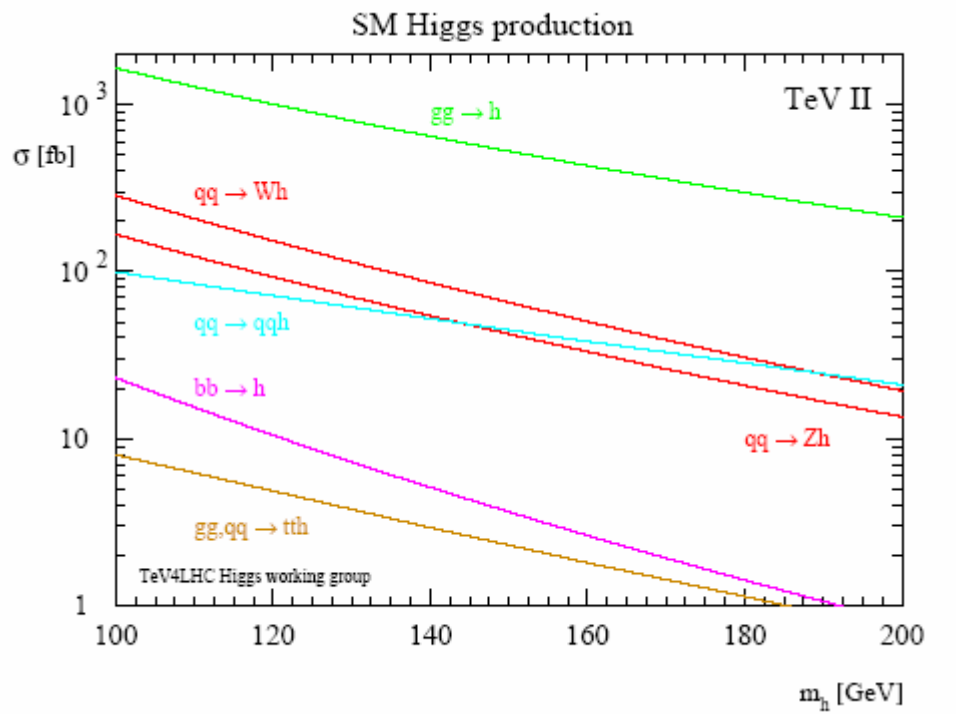


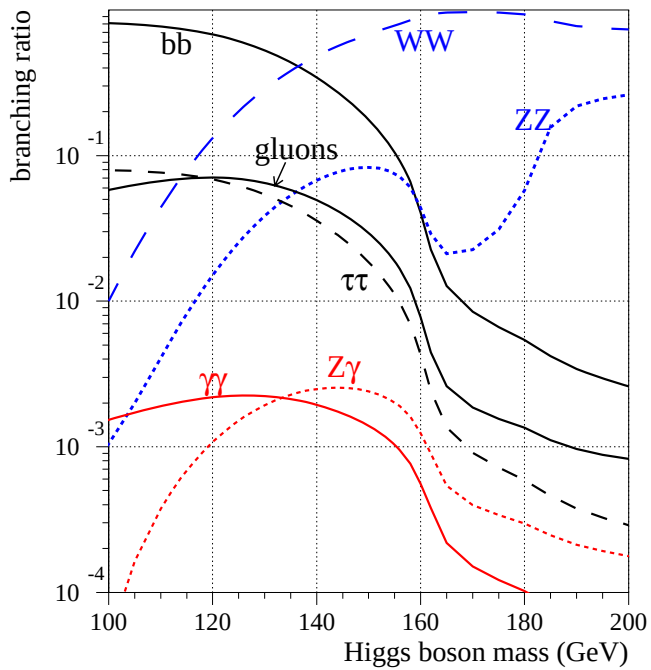


The Higgs boson at the Tevatron

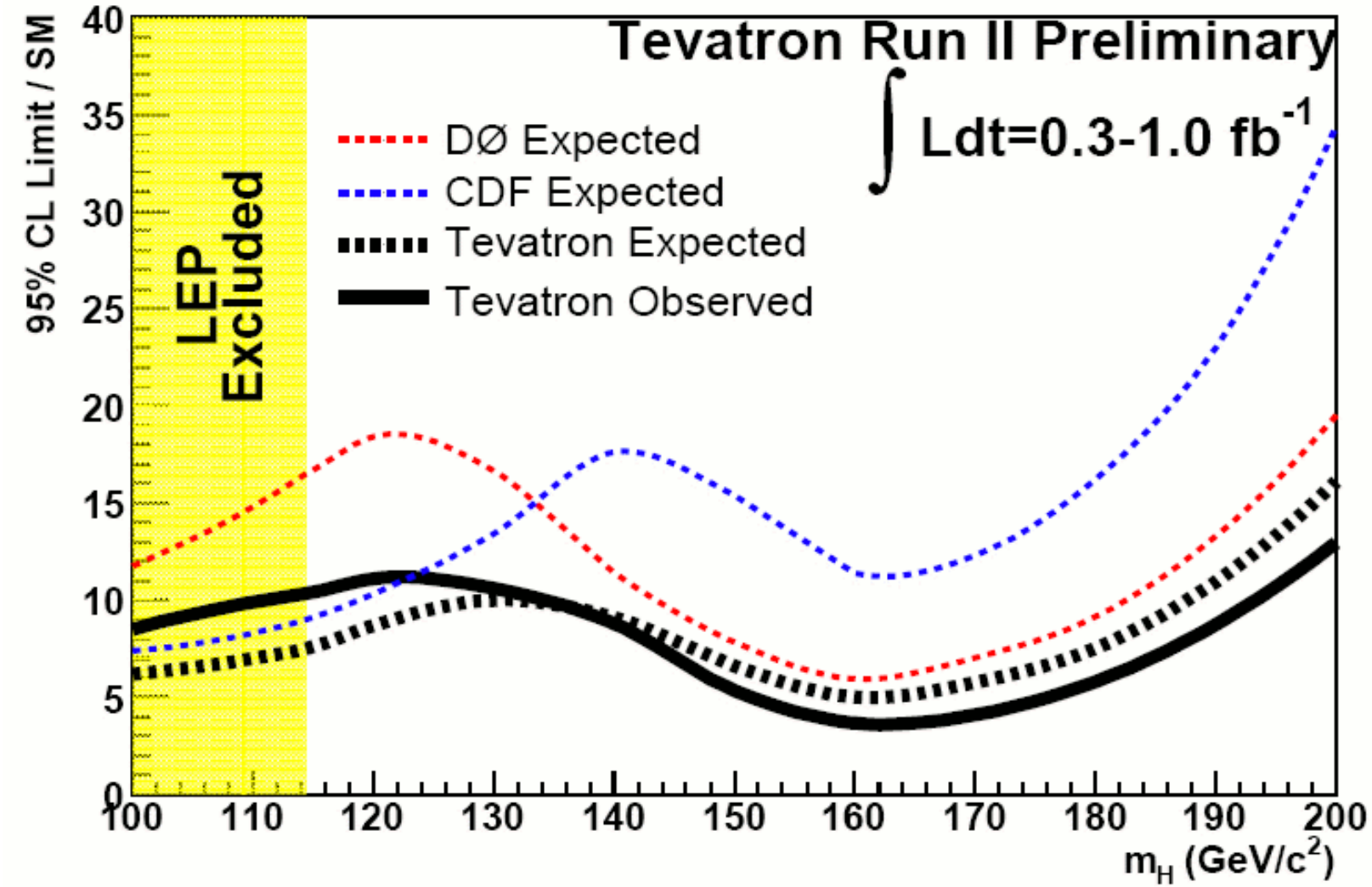
- **In high-energy proton-antiproton collisions the most significant signatures are three:**
  - **pp→WH→lνbb**
  - **pp→ZH→ llbb (ννbb)**
  - **pp→ H→ WW**
- Other channes can contribute only marginally to a combined result:
  - pp→WH→WWW, pp→ttH, VBF pp→qqH
- CDF and D0 have few chances of observing a unquestionable signal alone, the more so in a single channel.

  → Crucial is to combine information from all channels, and the results of the two experiments





SM Higgs: Tevatron combination

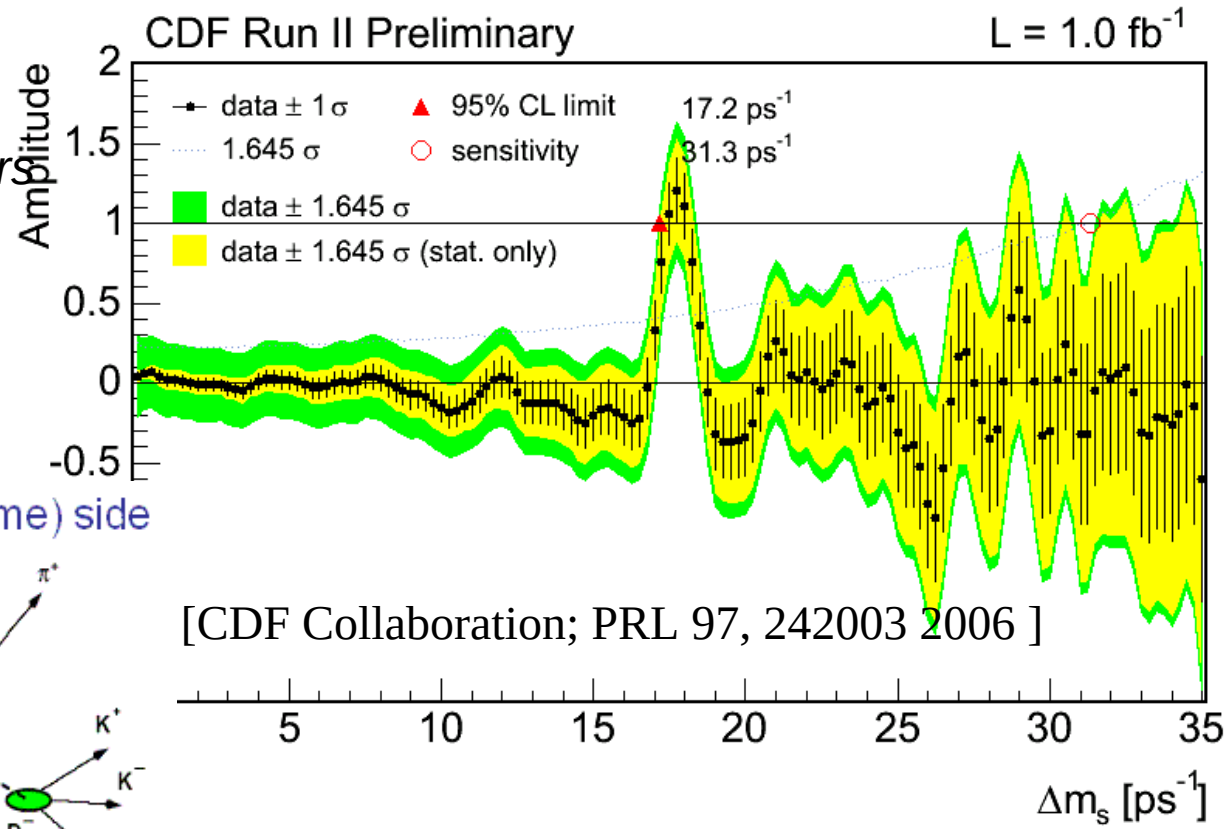


Bs oscillations

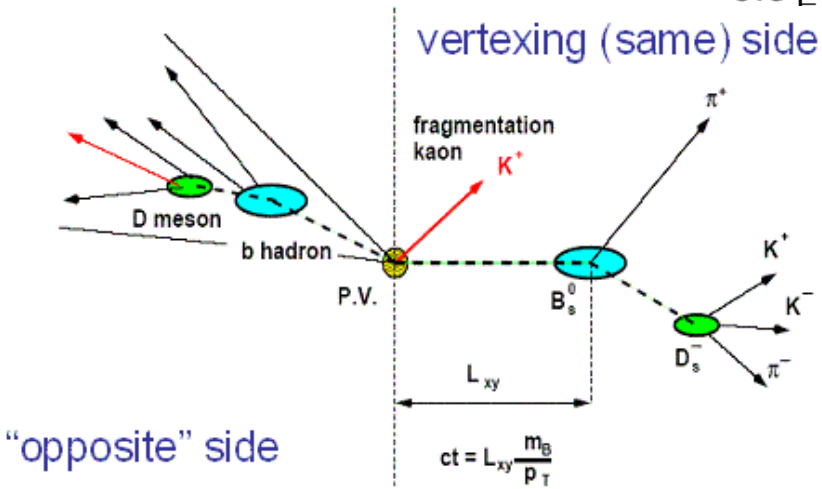
The analysis for the measurement of the oscillation amplitude was recently improved in CDF by
- selection based on NN, PID
- added partially reconstructed decay modes
- better combination of b-taggers

→ Result exceeding 5-sigma!

$$P(t;A)_{B_s \to \bar{B}_s} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm A\cos(\Delta m_s t))$$



[CDF Collaboration; PRL 97, 242003 2006]



$\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}

$|V_{td}|/|V_{ts}| = 0.2060 \pm 0.0007(\text{exp})\ ^{+0.0081}_{-0.0060}(\text{th})$

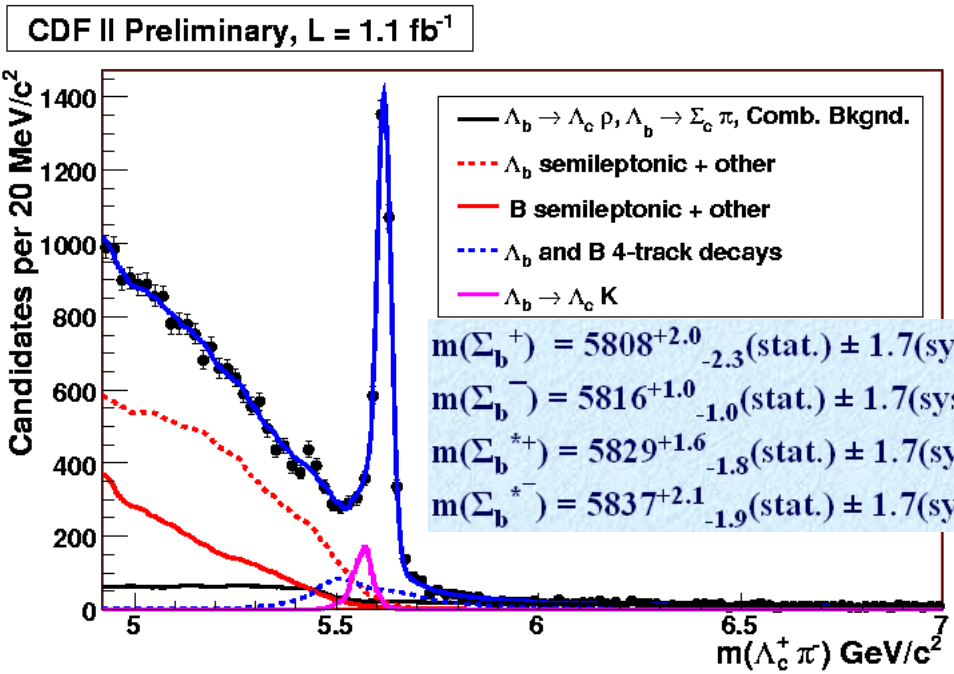
Discovery of Σ_b baryons

Fully reconstructed decays:

$$\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm; \quad \Lambda_b^0 \to \Lambda_c^+ \pi^-; \quad \Lambda_c^+ \to pK^-\pi^+$$

One more success for SVT

Masses in agreement with HQET

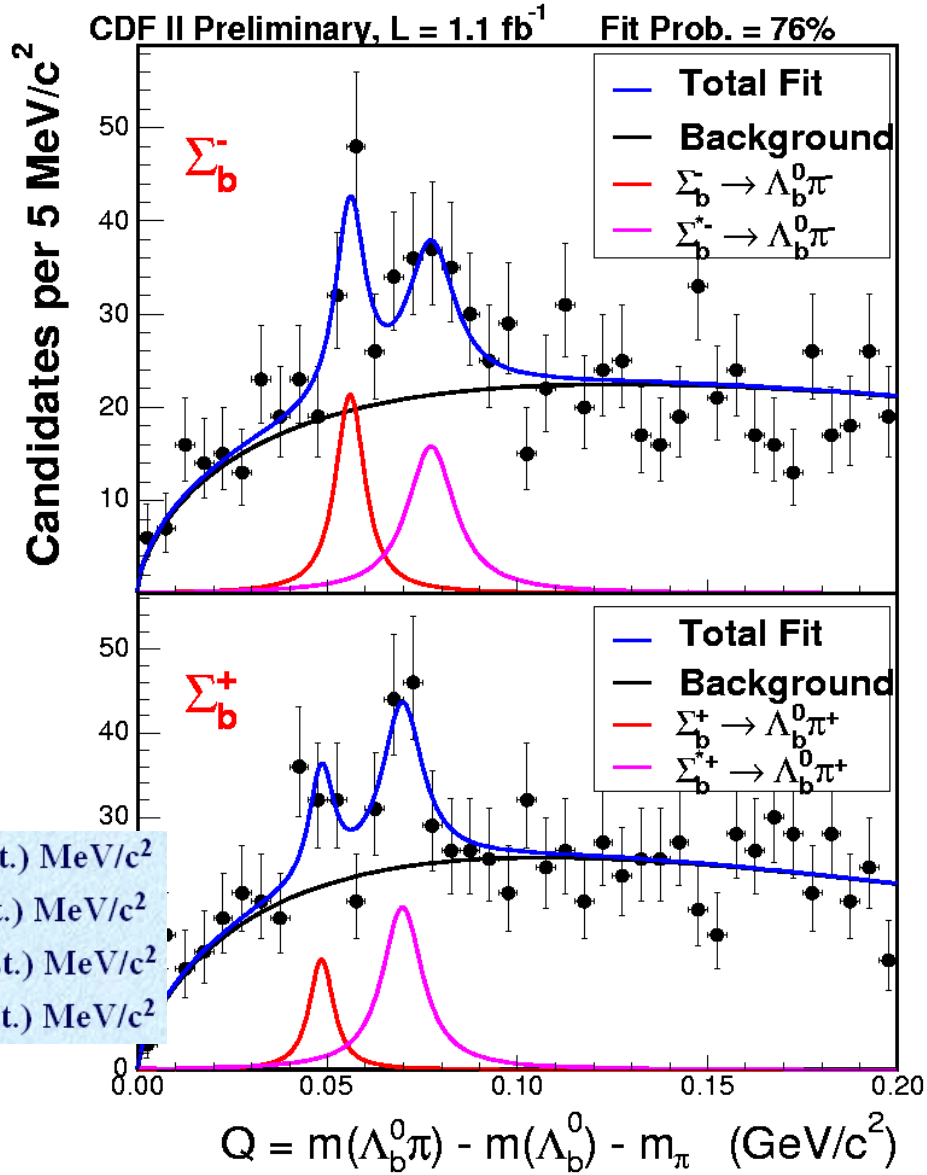


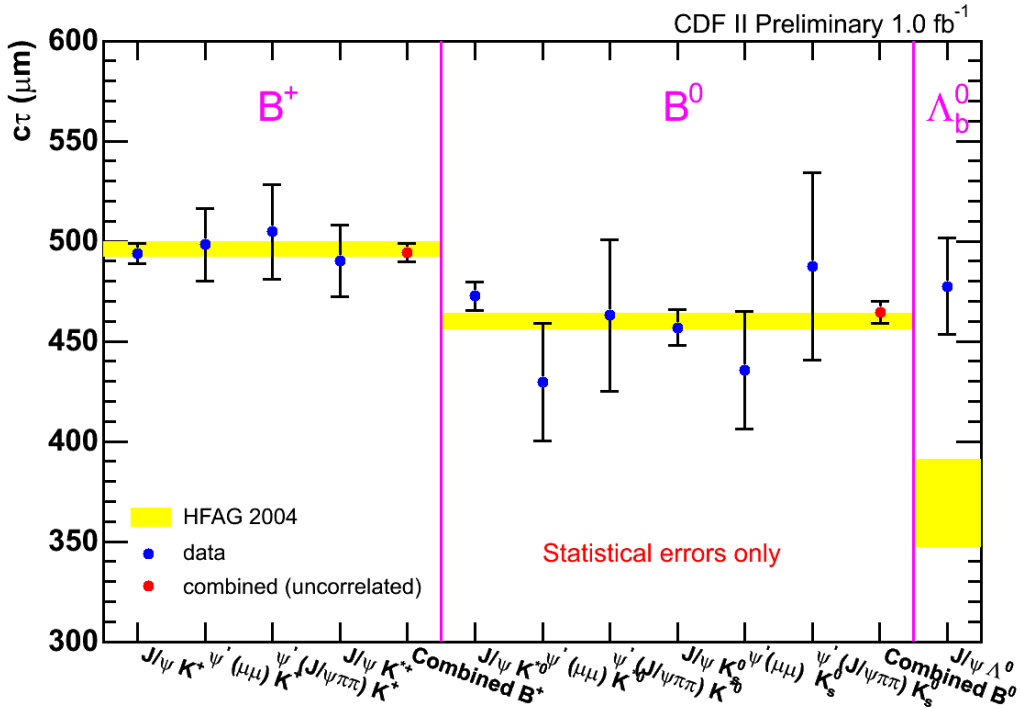
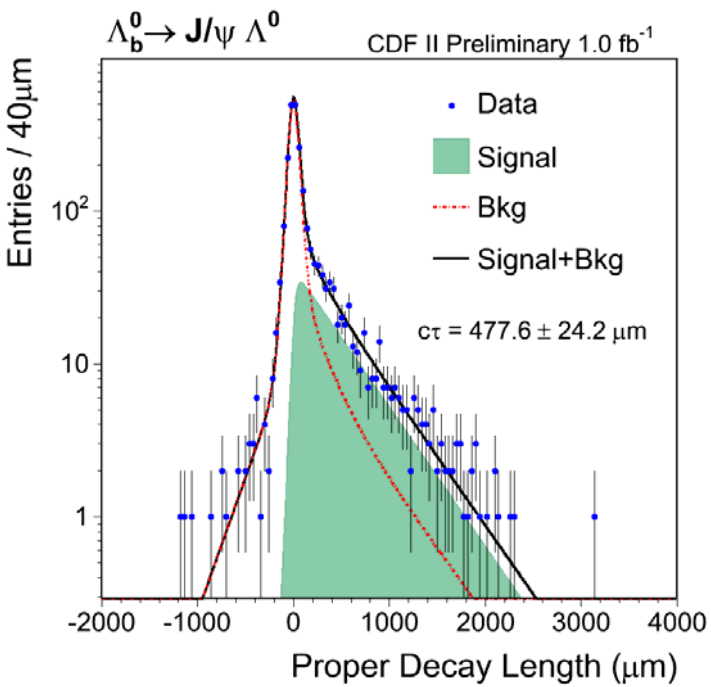
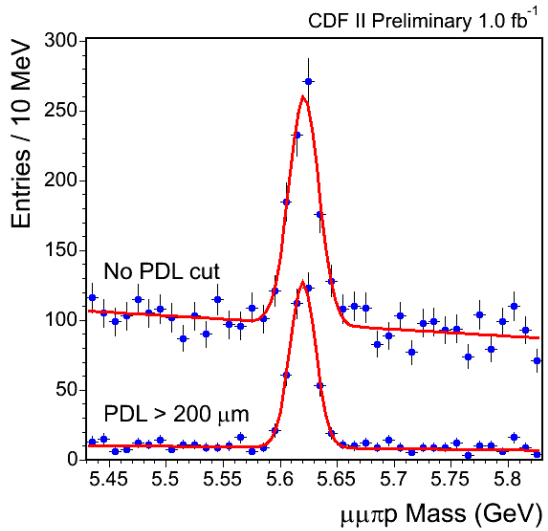
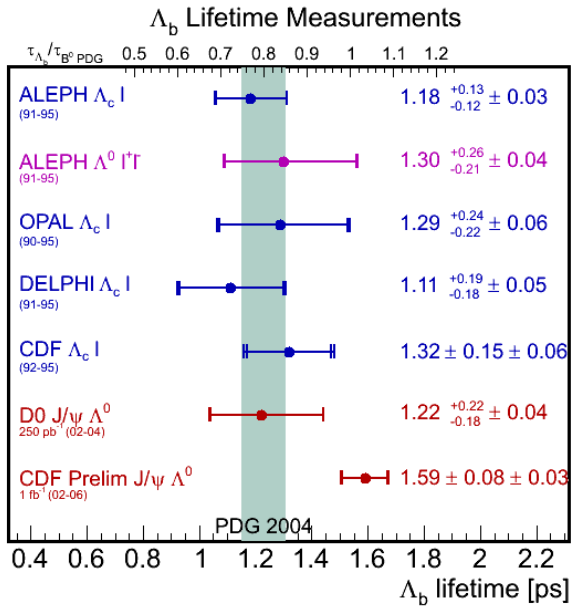
$m(\Sigma_b^+) = 5808^{+2.0}_{-2.3}(\text{stat.}) \pm 1.7(\text{syst.})$ MeV/c^2

$m(\Sigma_b^-) = 5816^{+1.0}_{-1.0}(\text{stat.}) \pm 1.7(\text{syst.})$ MeV/c^2

$m(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}(\text{stat.}) \pm 1.7(\text{syst.})$ MeV/c^2

$m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}(\text{stat.}) \pm 1.7(\text{syst.})$ MeV/c^2



B lifetimes

- CDF measures B° and B+ lifetimes in many different final states → **precise results in good agreement with world averages**
- Λ_b lifetime measurements obtained from fully reconstructed decays are more precise than previous ones and disagree with former average by 3.2σ
- Ratio of Λ_b and B° lifetimes is **R=1.041±0.057**, marginally in agreement with theoretical predictions